Equilibrium and transport properties of the quark-gluon plasma at the BES

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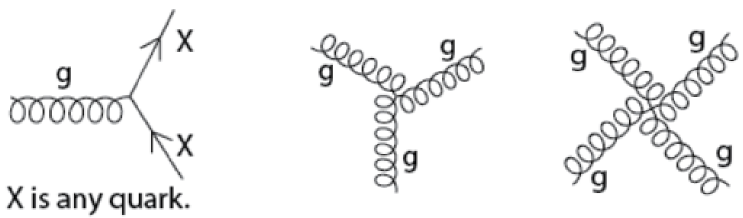
with R. Critelli, I. Portillo, R. Rougemont, J. Noronha-Hostler, and C. Ratti

PRL 115 (2015), JHEP 1604 (2016) 102, arXiv:1704.05558, **arXiv:1706.00455**

RHIC & AGS Annual Users' Meeting, BNL, June 2017

Quark-gluon plasma: The primordial liquid

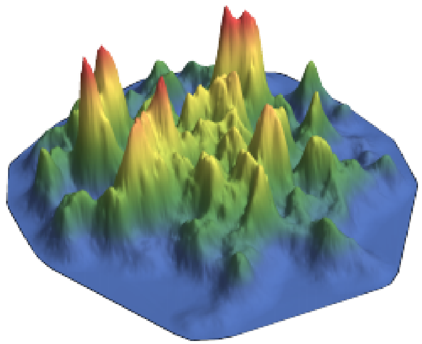
QCD $\rightarrow$ confinement + asymptotic freedom



gluon self-interactions

?

Quark-Gluon Plasma



Plot from Noronha-Hostler, Betz, Gyulassy, JN, PRL 2016

Perfect fluidity: $\frac{\eta}{s} < 0.2$ $\rightarrow$ emergent property of QCD at large T
and ~ zero net baryon density !

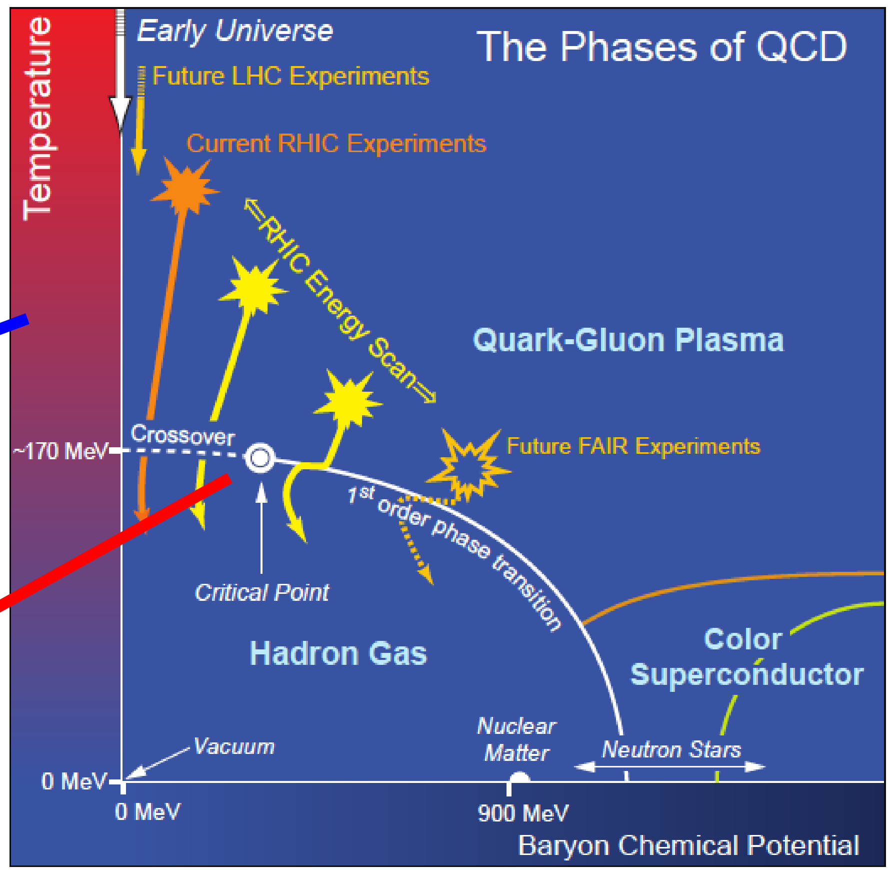
What happens to the primordial liquid in the baryon rich regime?

$$T \sim 100 - 150\,\mathrm{MeV} \qquad \frac{\mu_B}{T} > 3$$

QCD Phase diagram

Current cartoon showing the different phases of QCD

Crossover confirmed by lattice



THE REST OF THE PHASE DIAGRAM IS NOT KNOWN

Critical point ???

WHY ??

(3d Ising universality class)

The Fermi sign problem

Many-body systems at finite density: The Fermi sign problem

Equilibrium quantities computed using Monte-Carlo method

$$\langle \mathcal{M} \rangle = \frac{1}{Z} \int \mathcal{D}\Phi \, \mathcal{M}[\Phi] \, \exp\{-S[\Phi]\} \longrightarrow \langle \mathcal{M} \rangle = \frac{1}{N} \sum_c \mathcal{M}[\Phi^{(c)}]$$

Sample $\Phi^{(c)}$ using $\mathrm{Prob}[\Phi] = e^{-S[\Phi]}/Z$

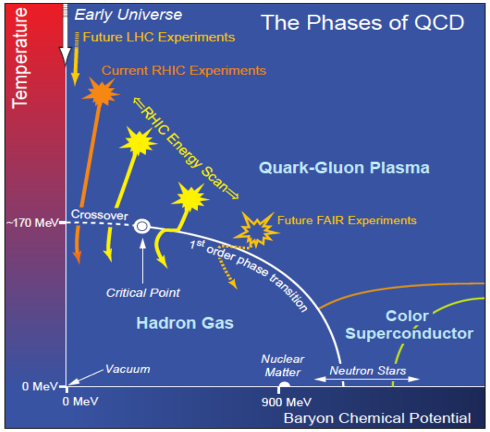
Fundamental problem when S is complex

This occurs in QCD at nonzero baryon chemical potential

$\mu_B \neq 0$

even though $Z(T, \mu_B)$ is well defined

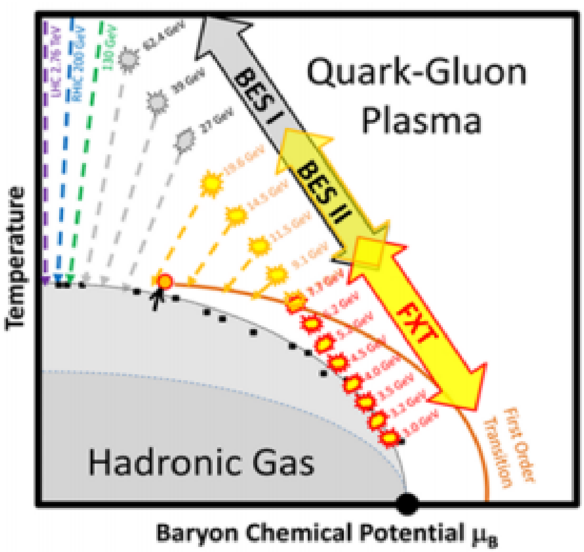
Consequences of the Fermi sign problem in QCD



- Majority of QCD phase diagram: unknown

- EOS of QCD matter in the core of compact stars: unknown

- Location of high T critical point: unknown



Immense discovery potential for the RHIC Beam Energy Scan (BES)

Major experimental effort to search for the critical point using heavy ion collisions (e.g., STAR)

QCD thermodynamics from a Taylor expansion

Expand the QCD partition function

$$Z(\mu_B,T) = \mathrm{Tr}\left(e^{-\frac{H_{\mathrm{QCD}}-\mu_B N_B}{T}}\right) = \int \mathcal{D}U e^{-S_G[U]} \det M[U,\mu_B]$$

in a Taylor series around $\mu_B = 0$

See S. Sharma's talk, Wed

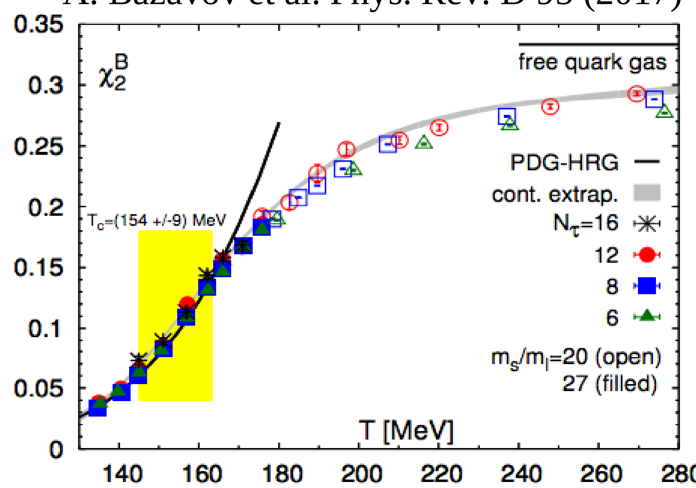
$$\boxed{\frac{P(T,\mu_B)-P(T,0)}{T^4} = \sum_{n=1}^{\infty} \frac{1}{(2n)!}\chi_{2n}(T)\left(\frac{\mu_B}{T}\right)^{2n}}$$

Baryon susceptibilities

$$\chi_n^B(T,\mu_B) = \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}$$

Few coefficients are known still at $\mu_B = 0$

A. Bazavov et al. Phys. Rev. D 95 (2017)



$\mu_B = 0$

QGP transport coefficients in the baryon rich regime

Now $\frac{\eta}{s} = \frac{\eta}{s}(T, \mu_B)$ and $\frac{\zeta}{s} = \frac{\zeta}{s}(T, \mu_B)$ + new transport coefficients

(shear) (bulk)

- Conserved currents: baryon, strange, electric $J^\mu_B, J^\mu_S, J^\mu_Q$

HIC $\mu_B > \mu_S > \mu_Q$

Diffusion of a conserved charge (e.g., baryon)

$$\left(\frac{\partial}{\partial t} - D_B \nabla^2 + \ldots\right) \rho_B = 0$$

Diffusion process

$$D = \frac{\sigma}{\chi_2}$$

D_B Baryon diffusion

σ_B Baryon conductivity

EMBEDDED IN HYDRODYNAMICS

How does one describe (nearly) perfect fluidity in a baryon rich QGP?

Model requirements:

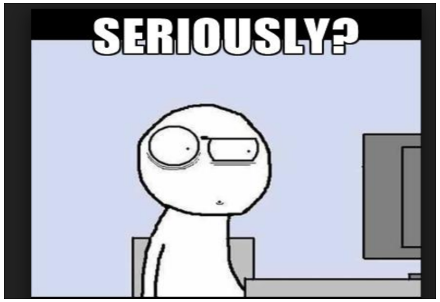
- Deconfinement

- Nearly perfect fluidity

- Agreement with lattice thermodynamics around crossover

- Agreement with lattice results for baryon susceptibilities at zero baryon density

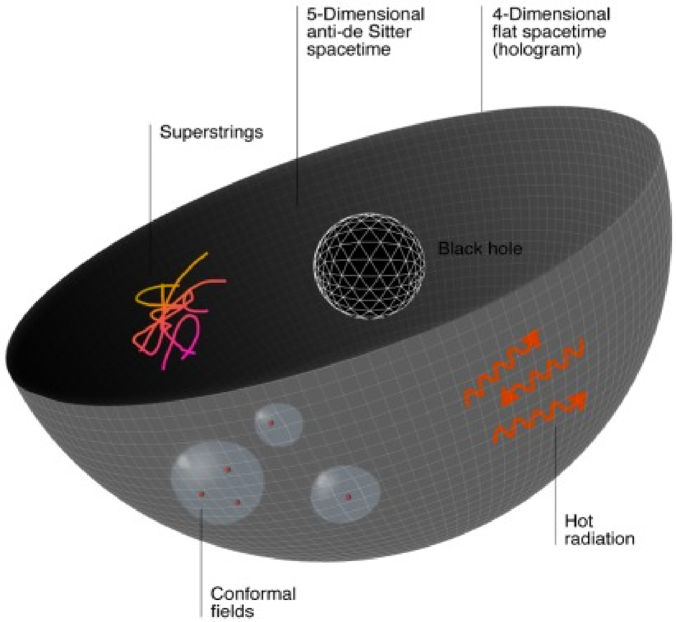
A WAY TO FULLFIL THESE CONDITIONS → BLACK HOLES



In science, it is better to ask for forgiveness than permission

Holography (gauge/string duality)

Maldacena 1997; Witten 1998; Gubser, Polyakov, Klebanov 1998



Strong coupling limit of QFT in 4 dimensions

⇕

String Theory/Classical gravity in d>4 dimensions

HOLOGRAPHIC PRINCIPLE

Universality and perfect fluidity

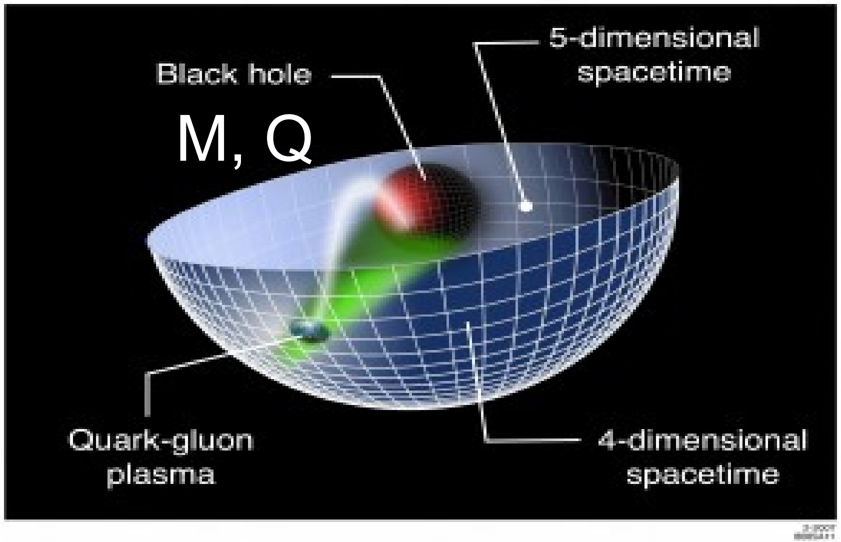
$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

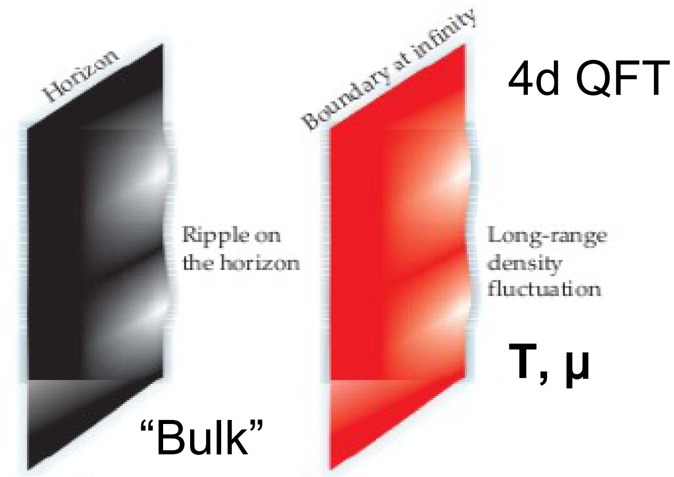
Natural framework for perfect fluidity

Kovtun,Son,Starinets, PRL 2005

The holographic correspondence at finite temperature and density

Near-equilibrium fluctuations in the plasma ~ black brane fluctuations !!!!





Thermodynamics / fluid dynamics from black hole physics

Quasiparticle dynamics replaced by geometry

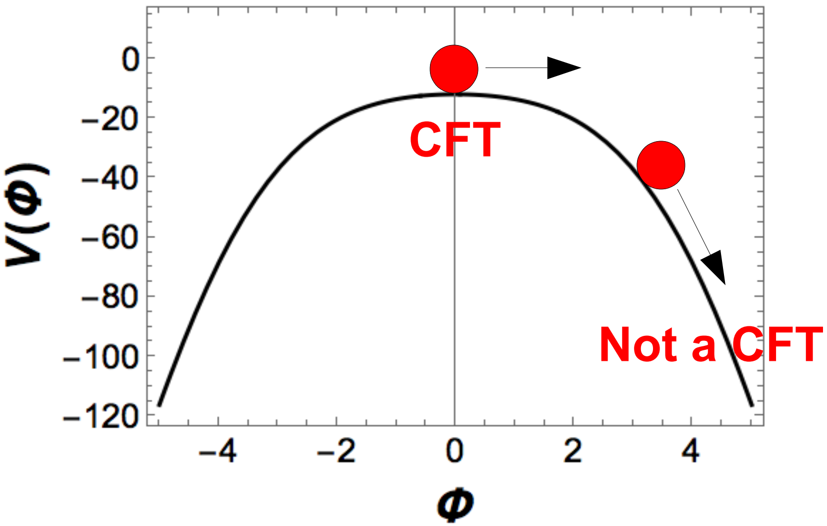
Black hole engineering and the non-conformal QGP

Minimal 5d holographic effective theory for a non-conformal plasma

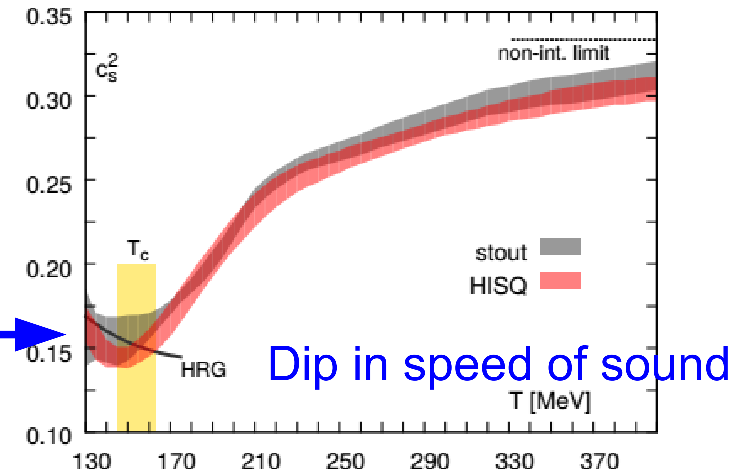
Gubser et al. 2008
Kiritsis et al, 2008
Noronha, 2009

$$S_{\mathrm{ES}}^{(\mathrm{bulk})} = \frac{1}{16\pi G_5}\int_{\mathcal{M}_5} d^5x\sqrt{-g}\left[R - \frac{(\partial_M \Phi)^2}{2} - V(\Phi)\right]$$

Φ is the scalar field and $V(\Phi)$ is the scalar potential



Non-conformal EOS

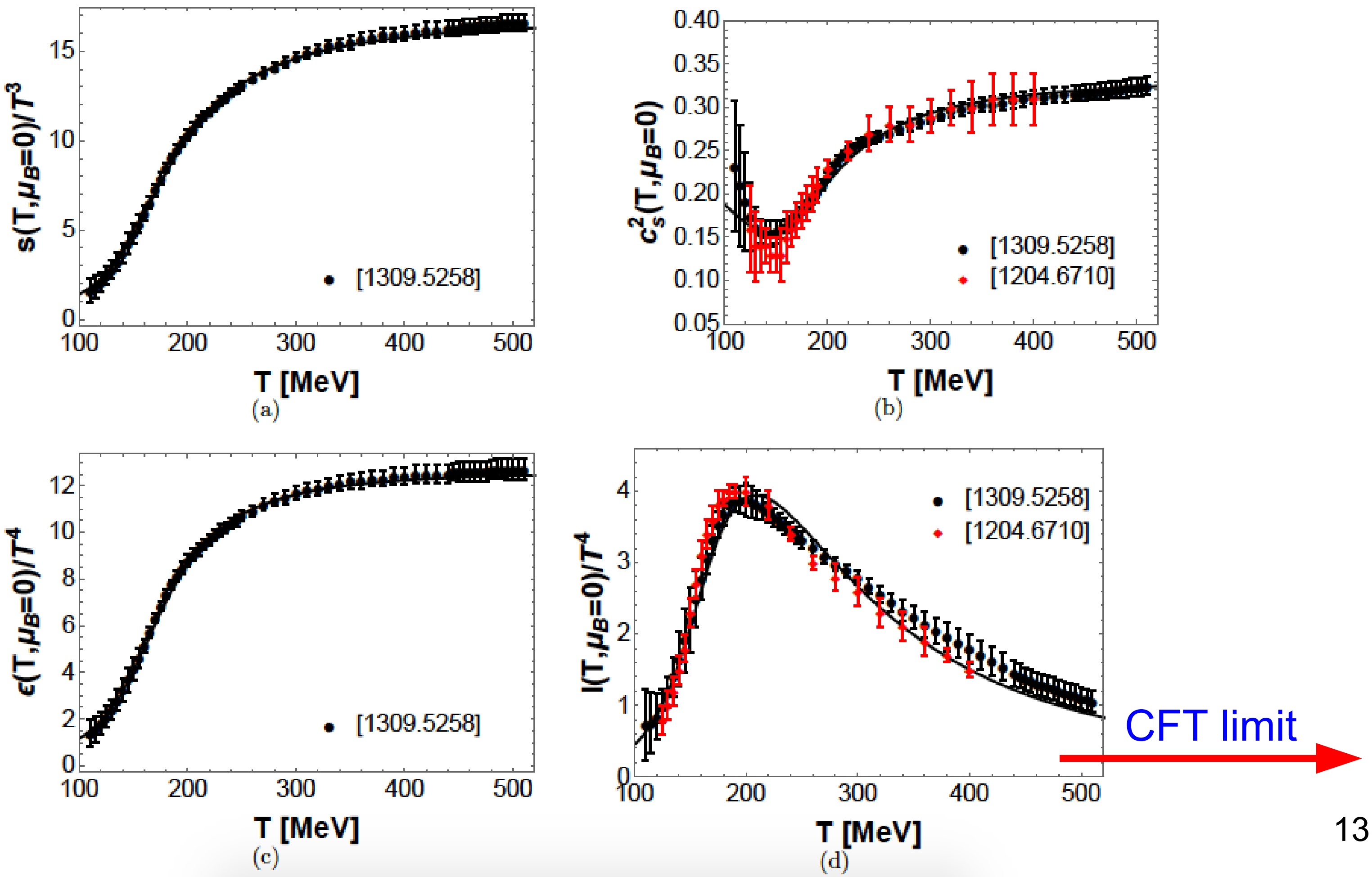


Lattice: HotQCD, Phys.Rev. D90 (2014) 094503

Black hole engineering and the non-conformal QGP

Excellent match to lattice results around crossover (zero baryon density)

arXiv:1706.00455



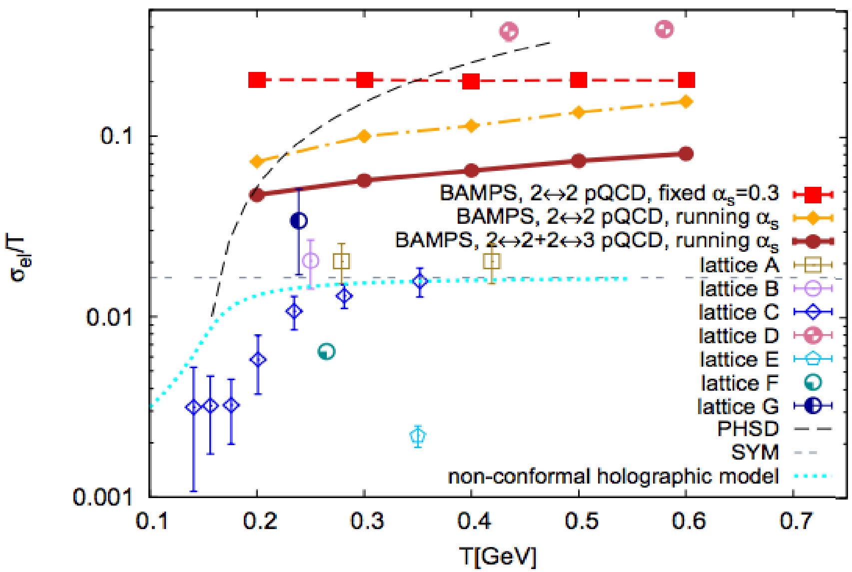
Black hole engineering and the non-conformal QGP

arXiv:1704.05558

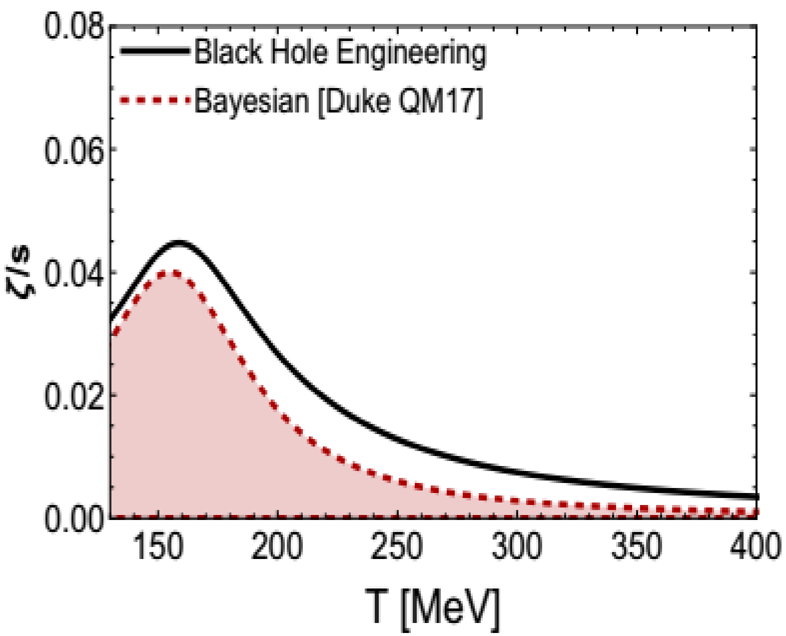
Transport coefficients

Electric conductivity

Greif et al., PRD D90 (2014)



Bulk viscosity

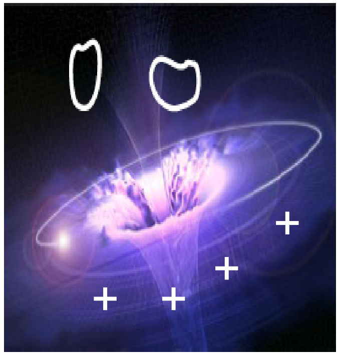


15+ other transport coefficients have also been computed

PRD 89 (2014), JHEP 1502 (2015), JHEP 1604 (2016), PRL 115 (2015)

“Doping” the holographic QGP with quarks

from R. Rougemont, J. Noronha-Hostler, JN, PRL 2015



Charged black hole

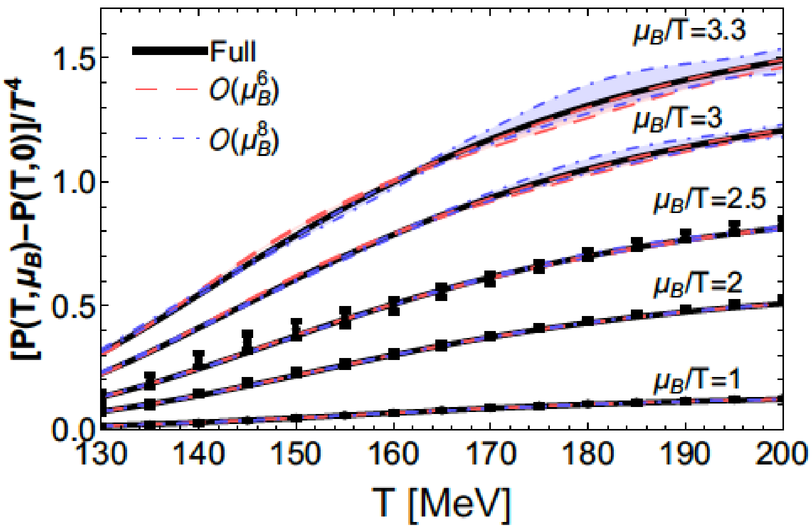
baryon charge → $Q_B \qquad \mu_B \neq 0$

Model matches latest lattice Taylor series results

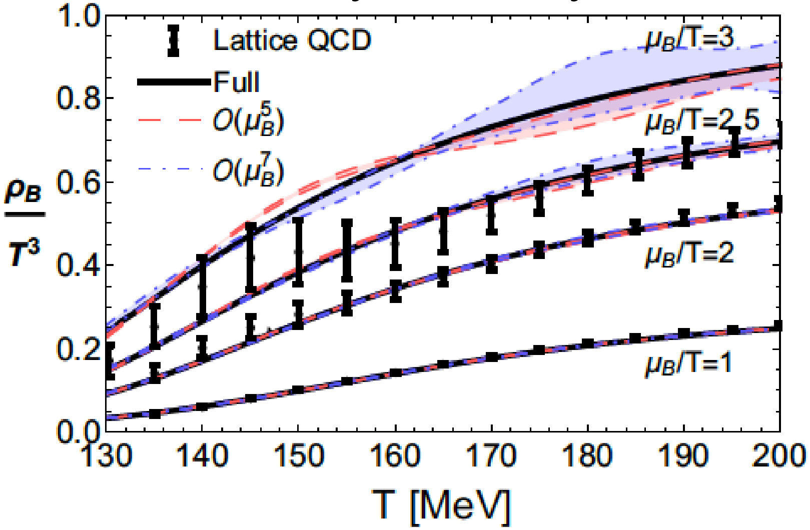
arXiv:1706.00455

Lattice = A. Bazavov et al. Phys. Rev. D 95 (2017)

Pressure difference



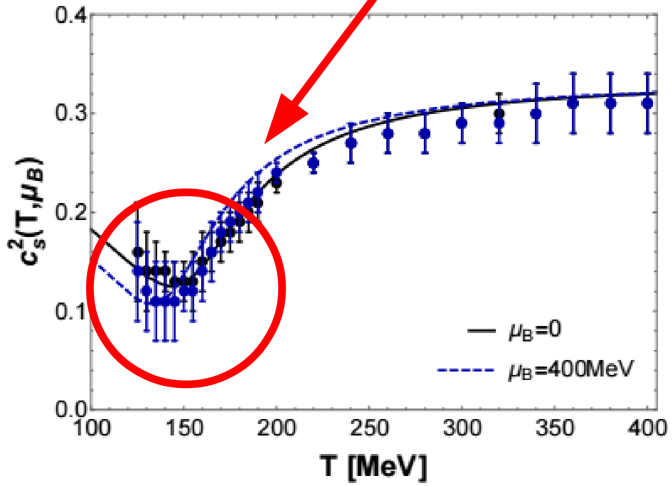
Baryon density

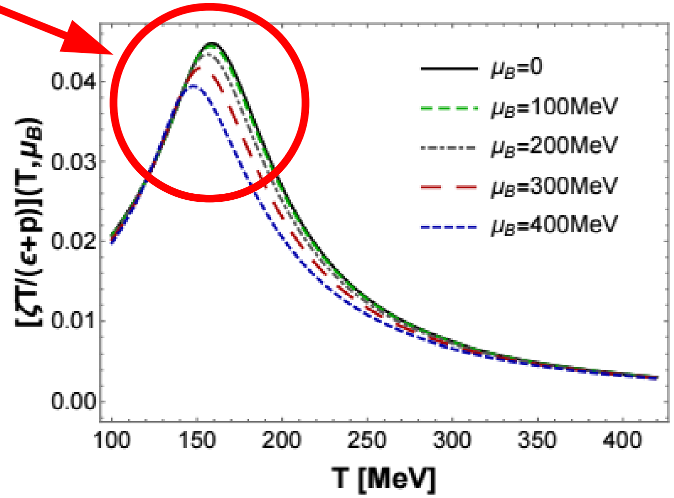


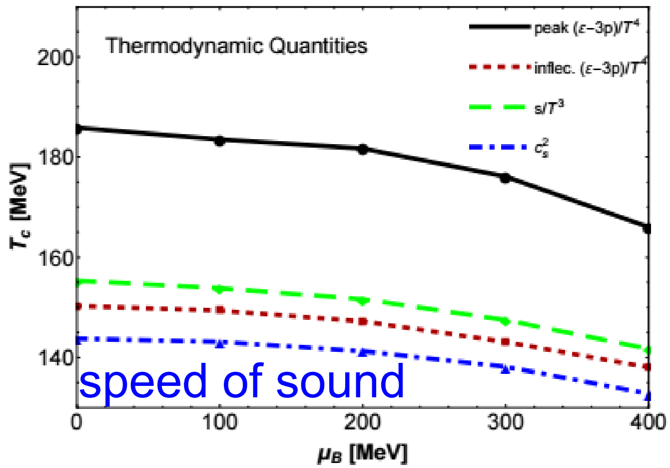
Dynamical vs. Equilibrium Properties of the Phase Transition

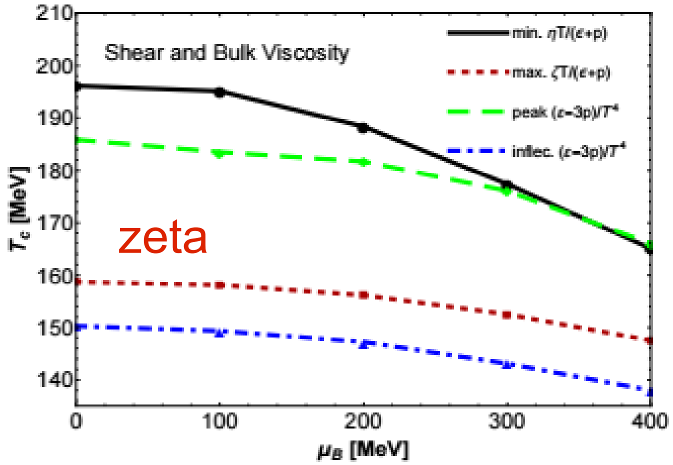
arXiv:1704.05558

How do these characteristic temperatures change with nonzero quark doping?





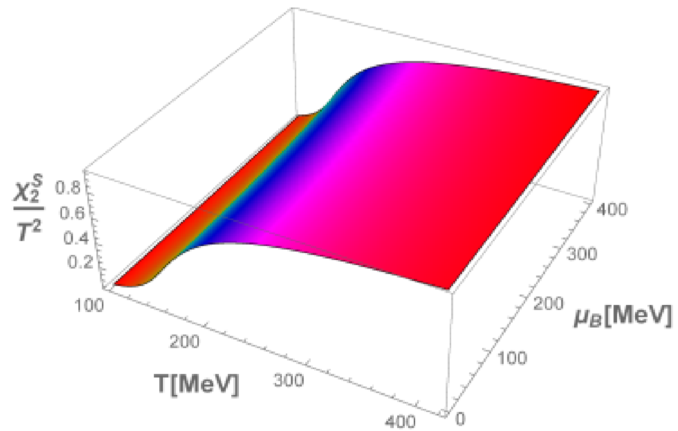




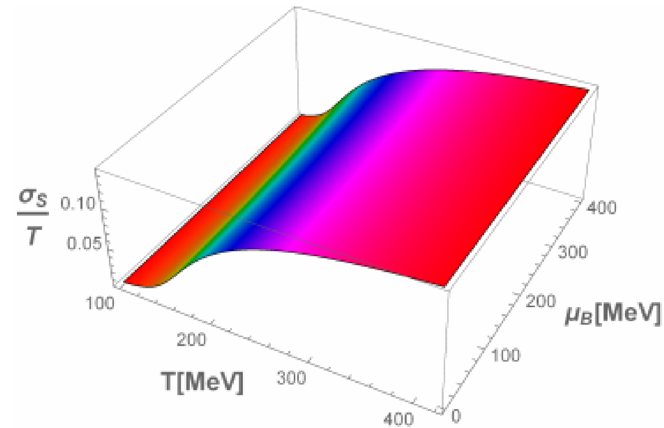
Dynamical vs. Equilibrium Properties of the Phase Transition

arXiv:1704.05558

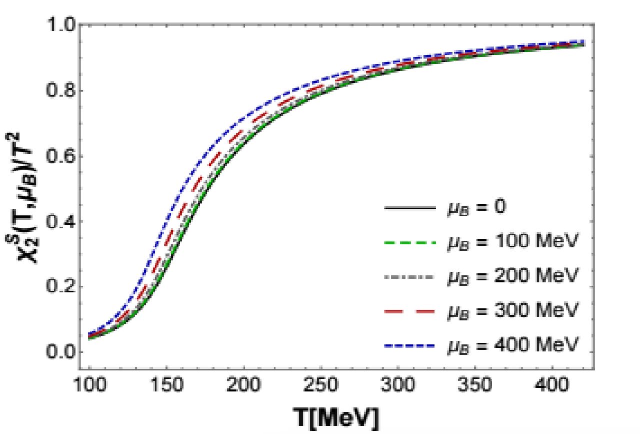
Transport of strangeness

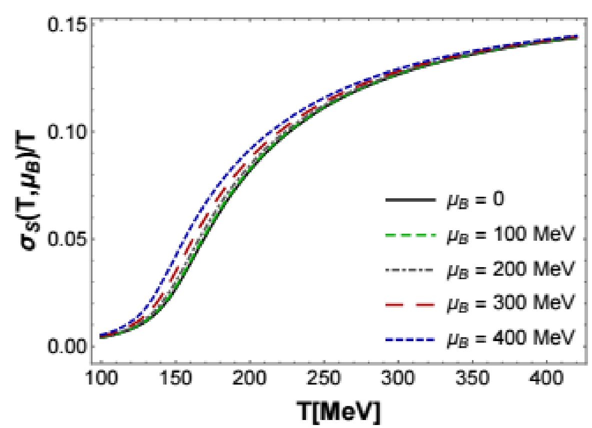


(a)



(a)





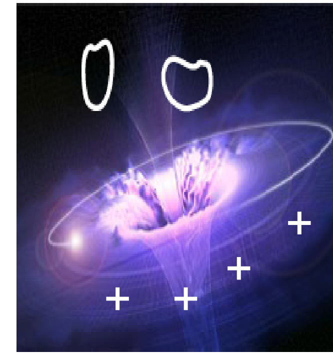
Strangeness susceptibility

Strangeness conductivity

Realistic calculations of baryon susceptibilities

Non-conformal holographic gravity dual in 5 dimensions $\Longrightarrow$ Black Hole Solution

$$\mathcal{S} = \frac{1}{16\pi G_5}\int dx^5 \sqrt{-g}\,[\mathcal{R} - \tfrac{1}{2}(\partial_M\phi)^2 - \underbrace{V(\phi)}_{\text{nonconformal}} \; \underbrace{-\tfrac{1}{4}f(\phi)F_{MN}^2}_{\mu_B\neq 0}]$$

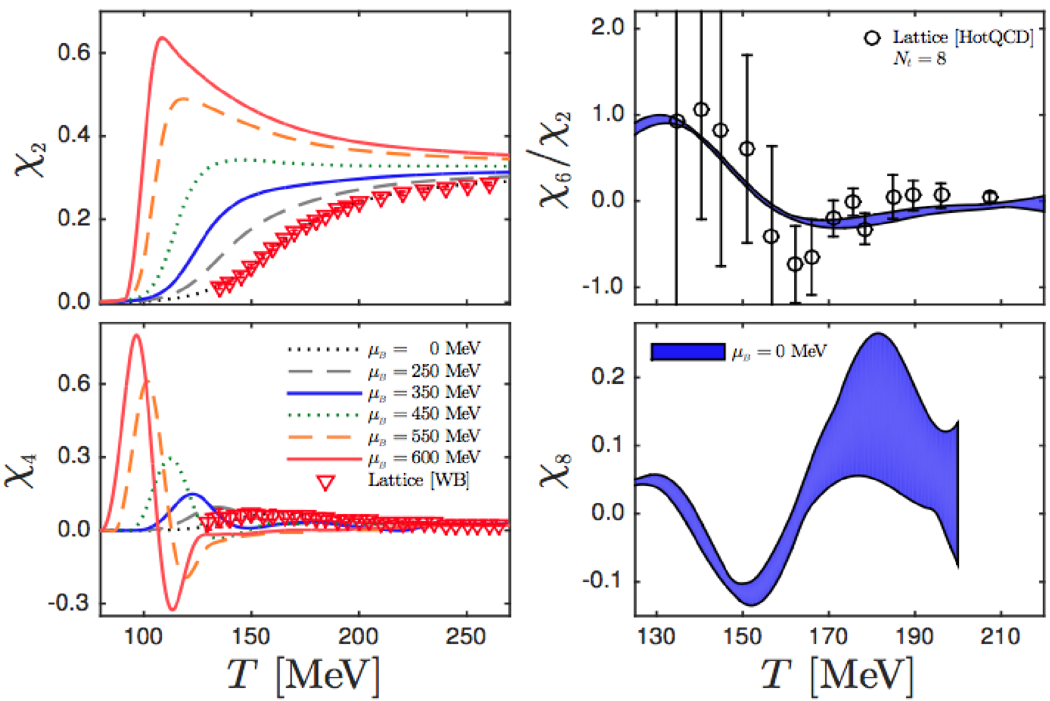


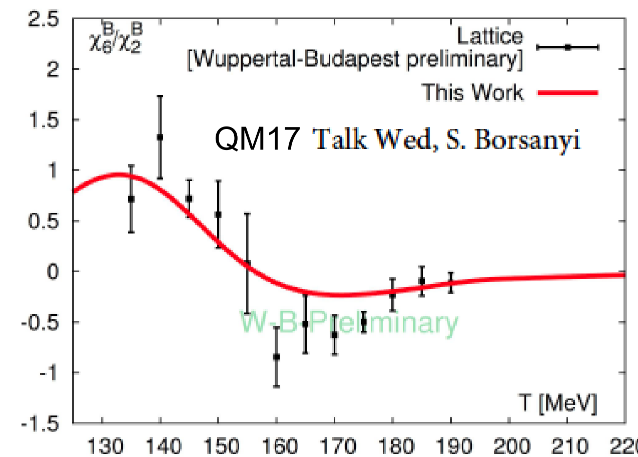
Charged black hole

arXiv:1706.00455

$$\boxed{\frac{\rho_B(T,\mu_B)}{T^3} = \sum_{n=1}^{\infty}\frac{1}{(2n-1)!}\chi_{2n}(T)\left(\frac{\mu_B}{T}\right)^{2n-1}}$$

2 million numerical black hole solutions !!

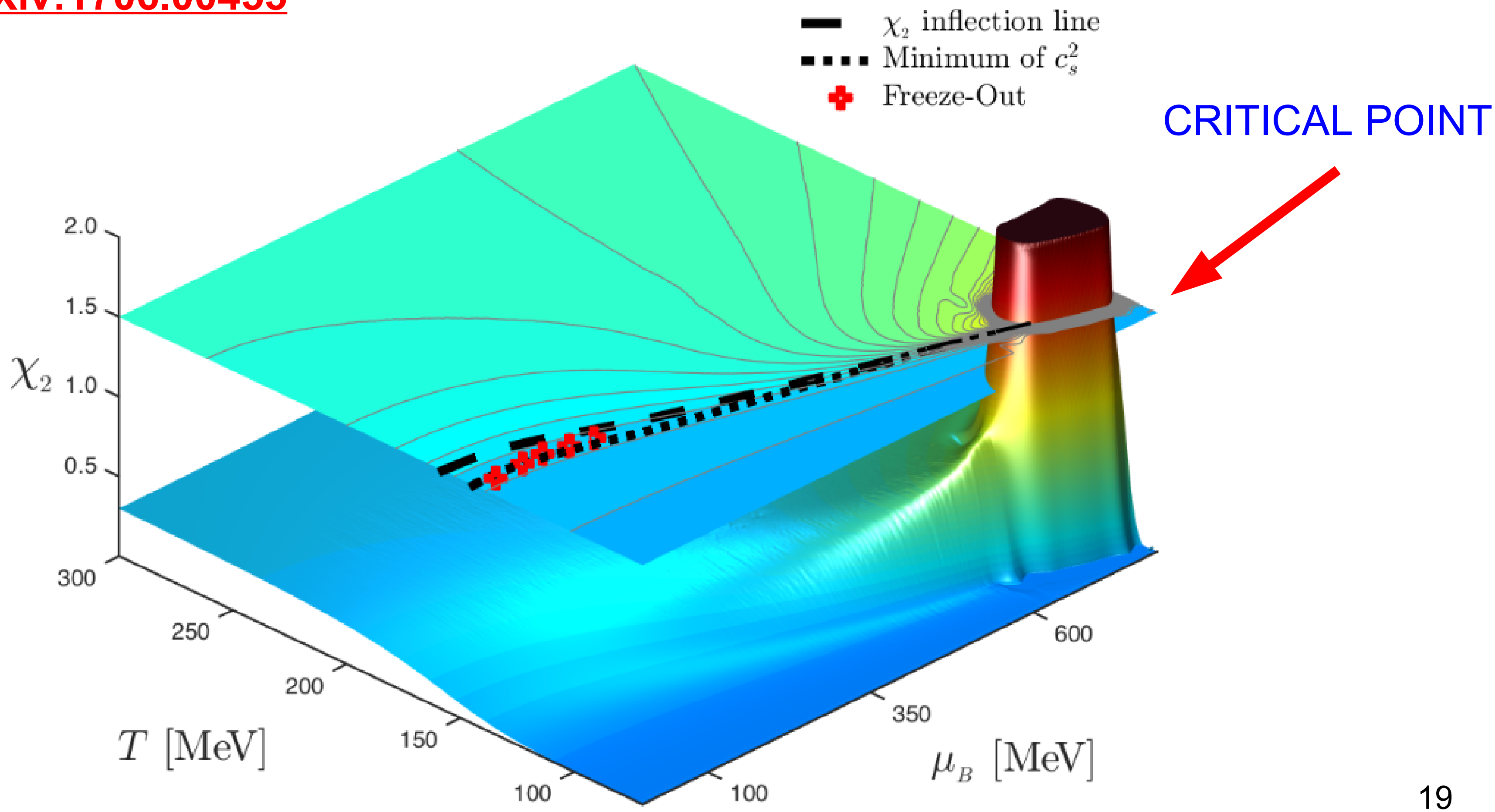




Location of the QCD critical point from black hole physics

Baryon susceptibility χ_2 diverges at: $T_{CEP} = 89\ \mathrm{MeV}, \quad \mu_B^{CEP} = 724\ \mathrm{MeV}$

arXiv:1706.00455

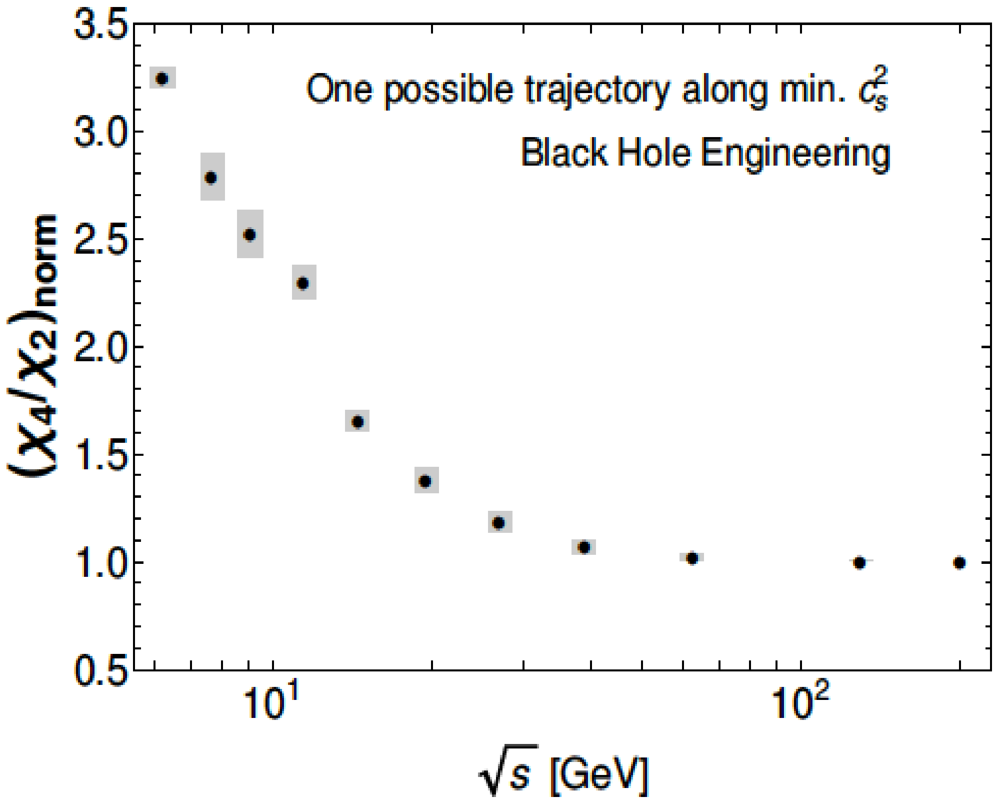


Prediction from black hole engineering

arXiv:1706.00455

Cumulants of the multiplicity of net baryons

$$\kappa\sigma^2 \sim \frac{\chi_4^B}{\chi_2^B}$$



Critical point located at:

$$\sqrt{s} = 2.5 - 4.1 \text{ GeV}$$

Non-monotonic behavior depends on chemical freeze-out trajectory (outside critical region)

This behavior can be checked at RHIC BES II. Other experiments?

Exclusion diagram for the location of the critical point

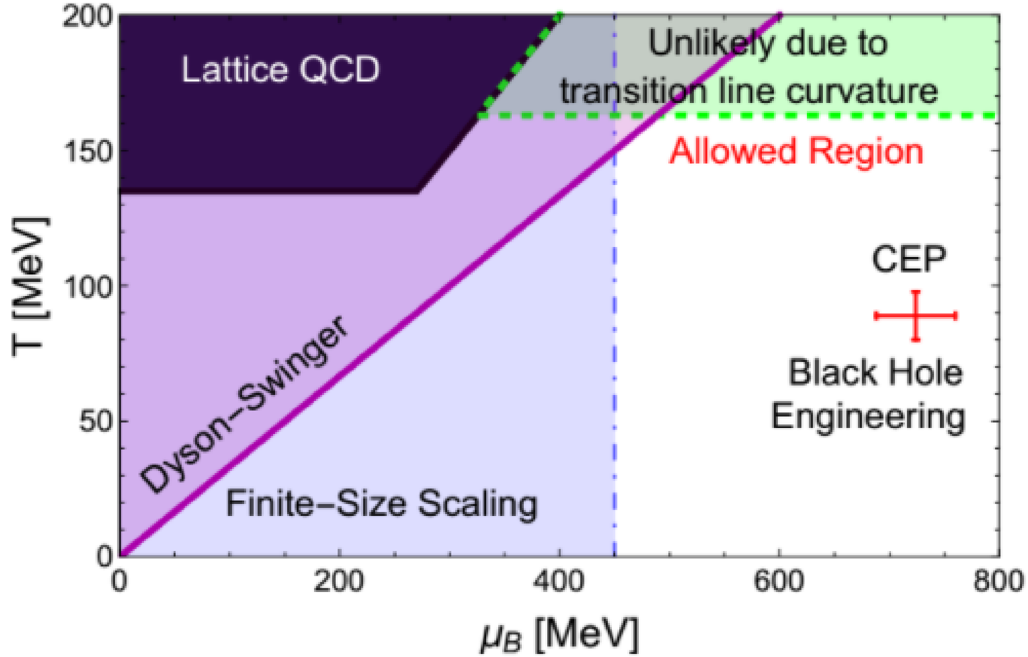


Diagram based on results from

- A. Bazavov et al. Phys. Rev. D 95 (2017)

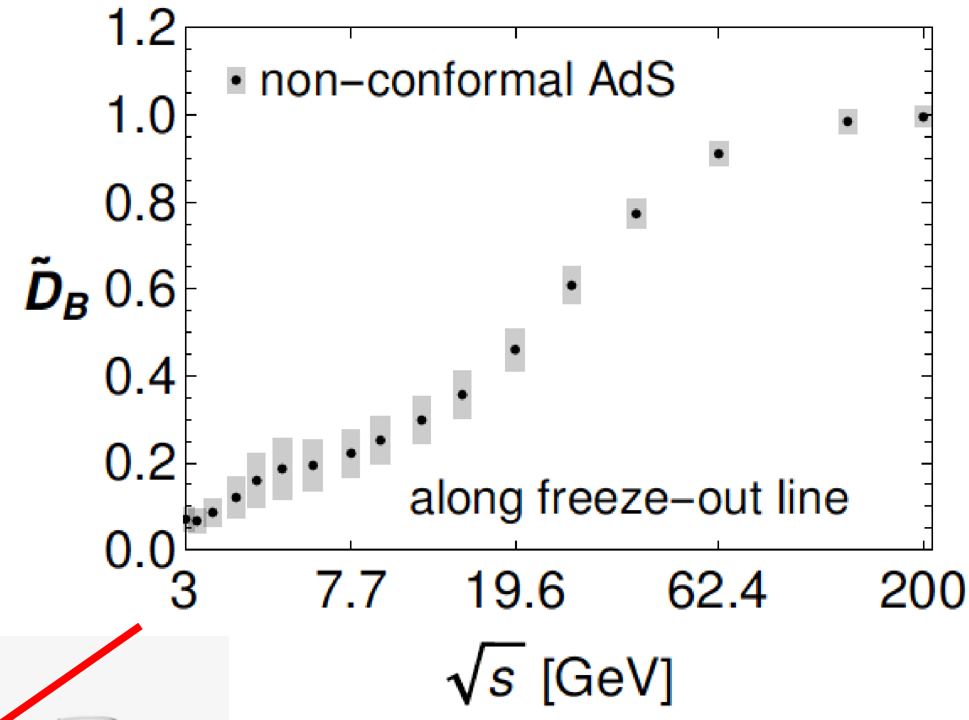
- Fraga, Palhares, Sorensen, Phys. Rev. C84 (2011)

- R. Bellwied et al., Phys. Lett. B751 (2015)

Suppression of baryon diffusion at the BES II

At critical point $\chi_2 \to \infty \Longrightarrow D_B \to 0$

Factor ~ 10 reduction in baryon diffusion at the BES II



Normalized by value at 200 GeV

Experimental / Phenomenological consequences??

Conclusions

- Physics of (holographic) black holes predict a critical point at

$$T_{CEP} = 89 \text{ MeV}, \quad \mu_B^{CEP} = 724 \text{ MeV}$$

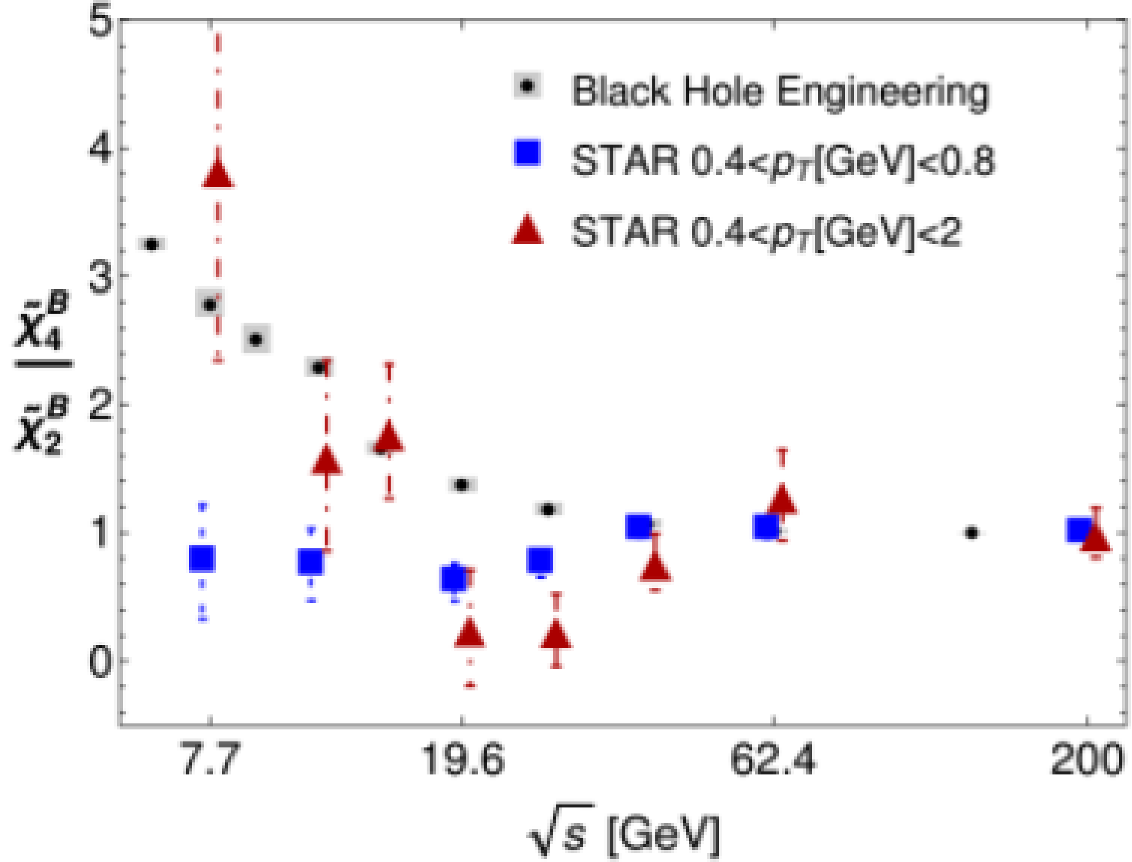
- This corresponds to $\sqrt{s} = 2.5 - 4.1 \text{ GeV}$

- Baryon charge gets “stuck” in the BES QGP liquid

- Characteristic temperatures of equilibrium and dynamical quantities have a wide spread in the crossover region

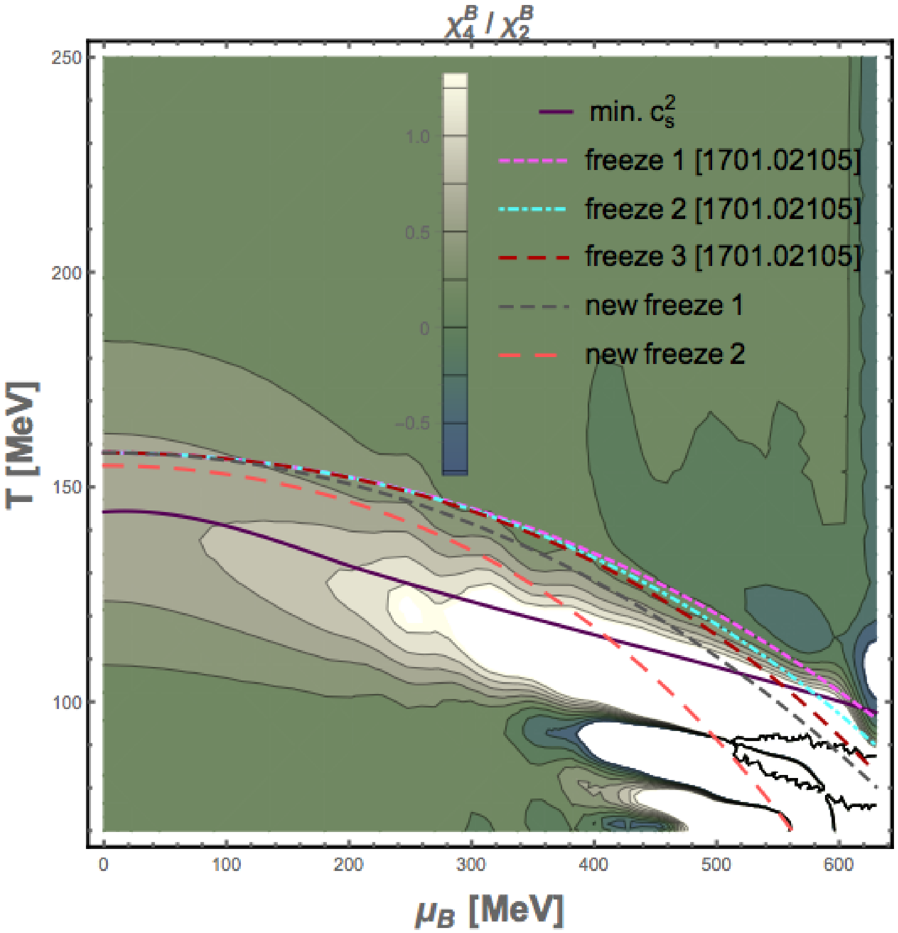
- Transport coefficients at zero baryon density within current estimates from hydro models (Bayesian analysis)

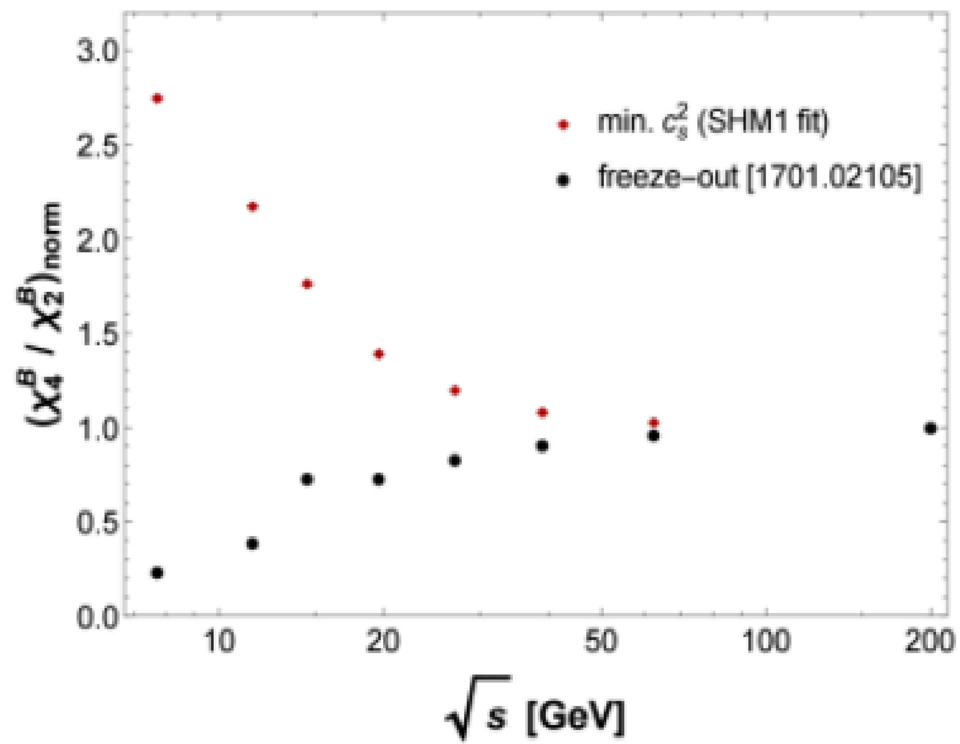
EXTRA SLIDES



Black Hole Engineering
STAR 0.4<p_T[GeV]<0.8
STAR 0.4<p_T[GeV]<2
$\frac{\tilde{\chi}_4^B}{\tilde{\chi}_2^B}$
5
4
3
2
1
0
7.7
19.6
62.4
200
$\sqrt{s}$ [GeV]

Dependence on the chemical freeze-out trajectory





- Start with a nontrivial UV fixed point – strongly interacting CFT.

- Add a relevant scalar operator → nontrivial IR behavior

- The scalar potential is an **input** of the theory

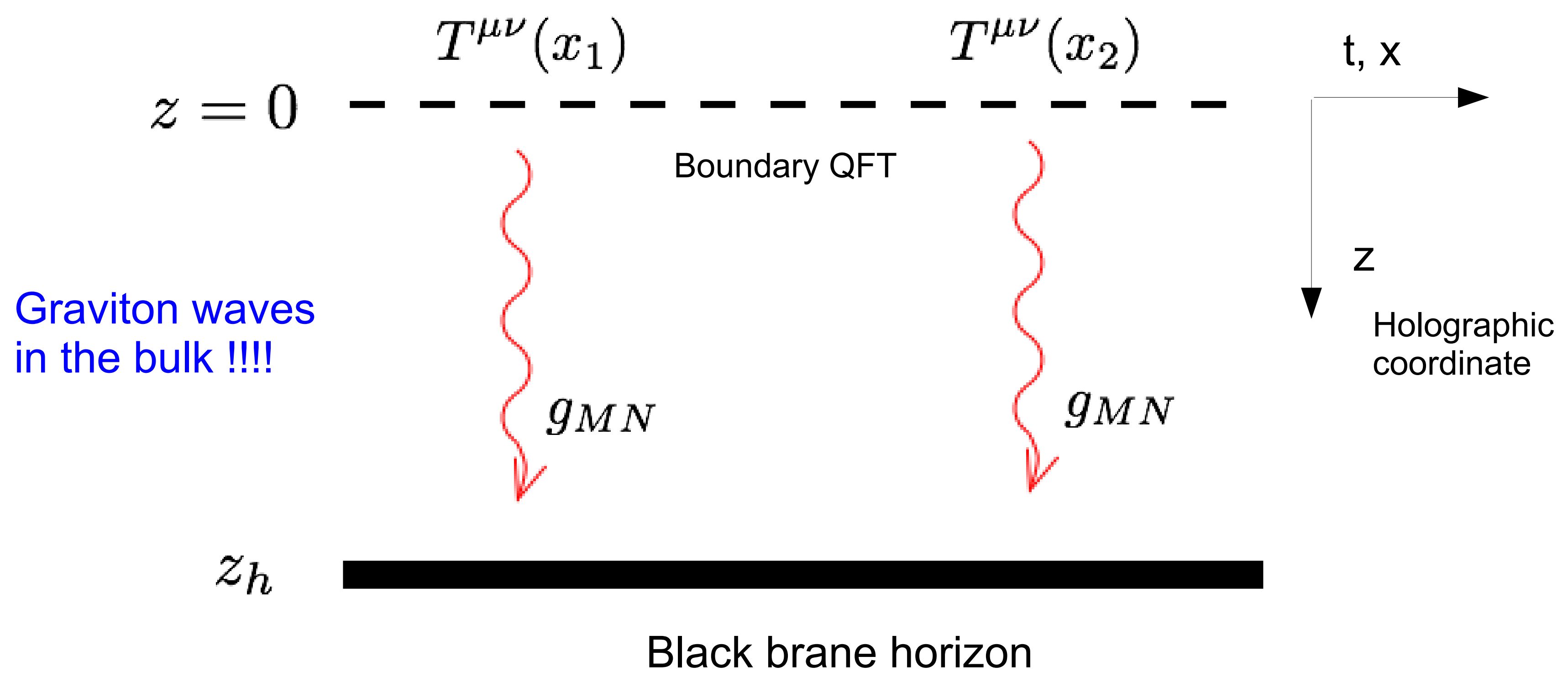
$$V(\Phi) = \frac{-12\cosh\gamma\Phi + b_2\Phi^2 + b_4\Phi^4 + b_6\Phi^6}{L^2}$$

$\gamma = 0.63,\ b_2 = 0.65,\ b_4 = -0.05,\ b_6 = 0.003$

completely fixed by requiring that the model describes lattice QCD results at finite T (and zero baryon density)

- Why is this useful for QGP physics?

Retarded correlator of the energy-momentum tensor $G_R^{xy,xy}$



Universality and perfect fluidity

$\lambda \gg 1$ in QFT $\rightarrow$ string theory in weakly curved backgrounds

d.o.f. / vol. $\rightarrow \infty$ in QFT $\rightarrow$ vanishing string coupling

T, μ in QFT $\rightarrow$ spatially isotropic black brane

For anisotropic models
there is violation
see arXiv:1406.6019

$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

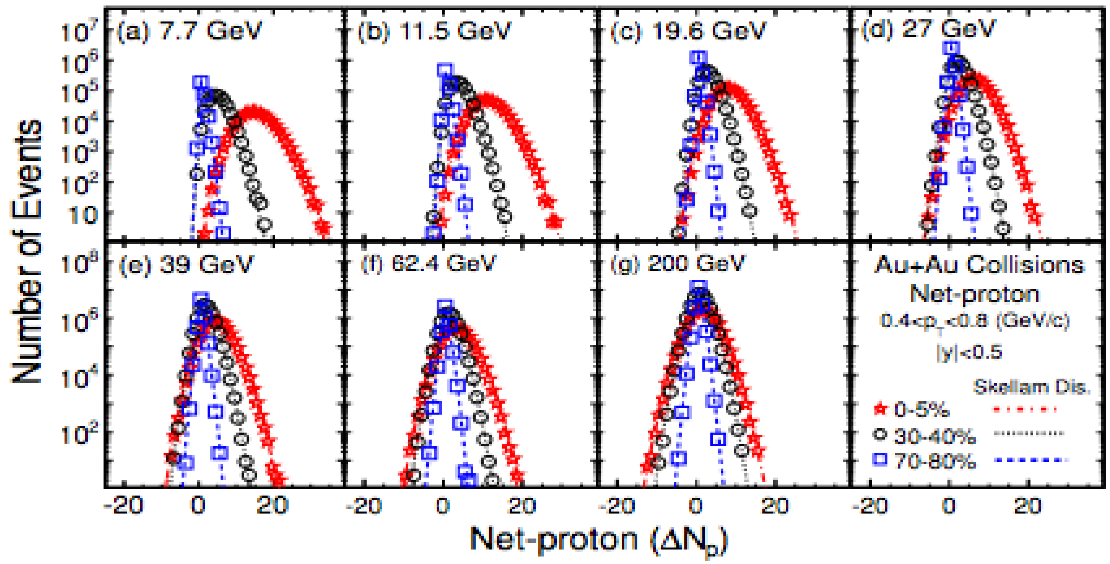
Universality of shear viscosity

Kovtun,Son,Starinets, PRL 2005

Universality of black hole horizons $\Rightarrow$ **HOLOGRAPHY** $\Rightarrow$ Universality of transport coefficient in QFT

Connecting the BES scan to theory

Fluctuations of net protons (STAR)



mean : $M = \chi_1$ variance : $\sigma^2 = \chi_2$

skewness : $S = \chi_3/\chi_2^{3/2}$ kurtosis : $\kappa = \chi_4/\chi_2^2$

$S\sigma = \chi_3/\chi_2$ $\kappa\sigma^2 = \chi_4/\chi_2$

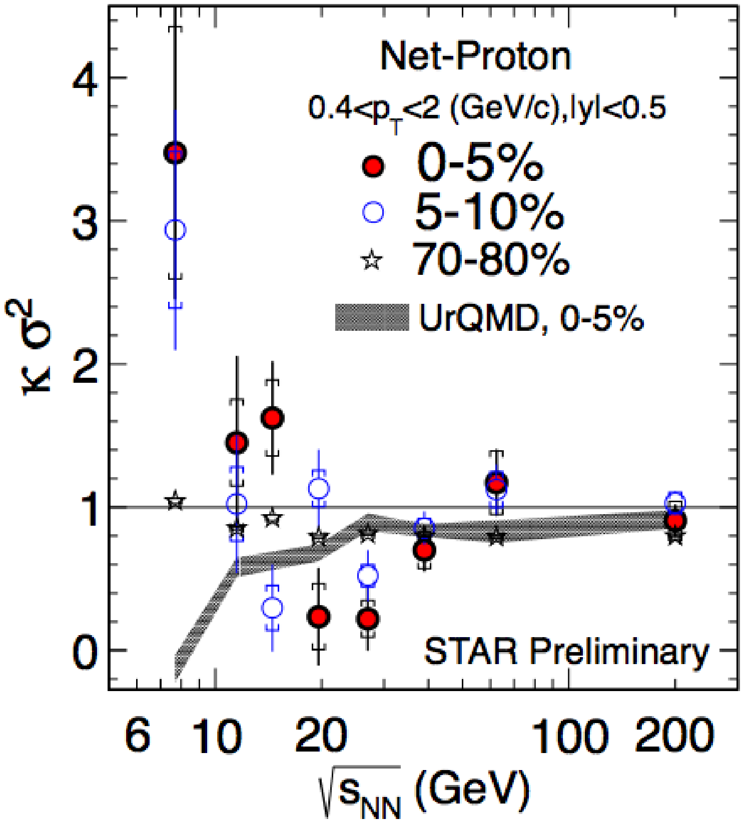
$M/\sigma^2 = \chi_1/\chi_2$ $S\sigma^3/M = \chi_3/\chi_1$

Cumulants of event-by-event distributions

Data / theory comparison

Current status from BES experimental data

X. Luo (2016)



$\kappa\sigma^2 = C_4/C_2$

Ratio of cumulants of net proton distributions

$$\boxed{\kappa\sigma^2 \sim \frac{\chi_4^B}{\chi_2^B}}$$

Baryon number susceptibilities

$$\chi_n^B(T,\mu_B) = \frac{\partial^n(P/T^4)}{\partial(\mu_B/T)^n}$$

This quantity should be large near the critical point

Many-body systems at finite density: The Fermi sign problem

This problem appears in QCD at nonzero baryon chemical potential

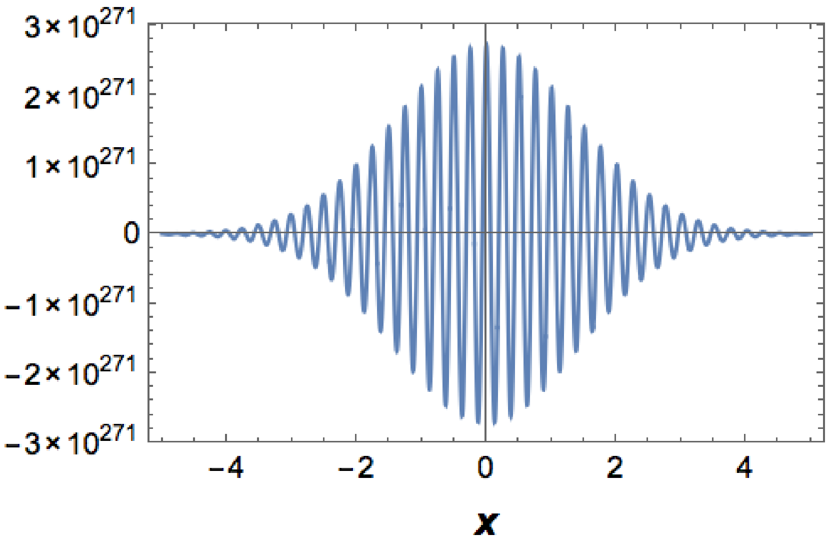
$$\mu_B \neq 0$$

Even though $Z(T, \mu_B)$ is well defined

Example: $\int_{-\infty}^{\infty} dx\, e^{-(x+ia)^2/4} = 2\sqrt{\pi}$

argument from G. Basar

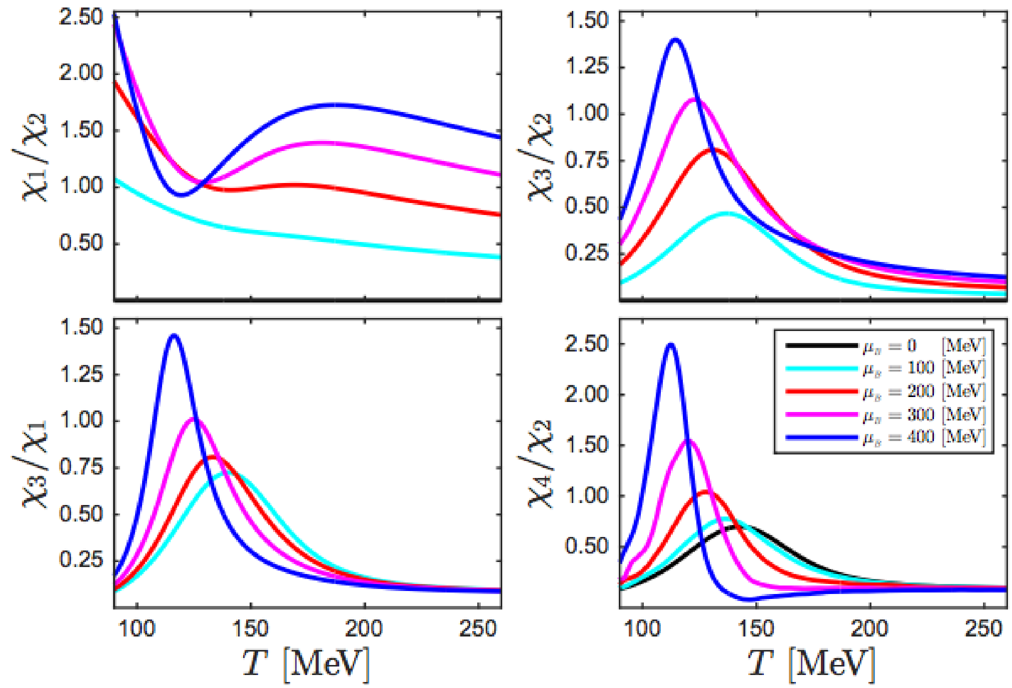
$$\mathrm{Re}\{e^{-(x+i\,50)^2/4}\}$$

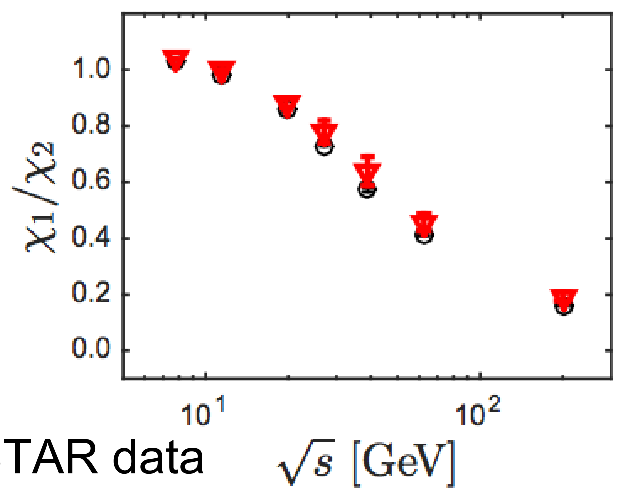


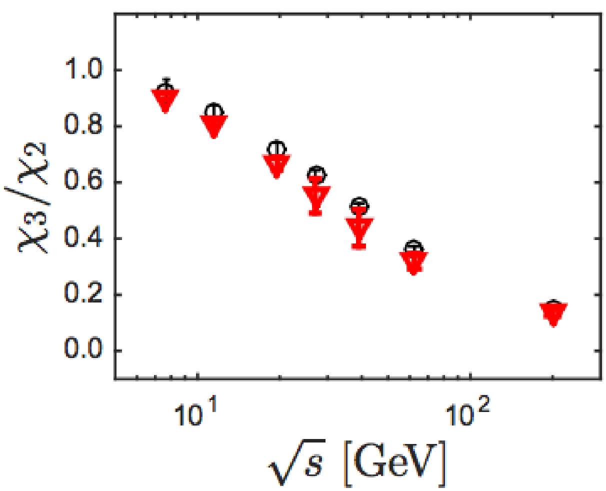
Many-body problem with exponential complexity

Troyer, Wiese, PRL 94, 170201 (2005)

Chemical freezeout parameters extracted from comparison to data



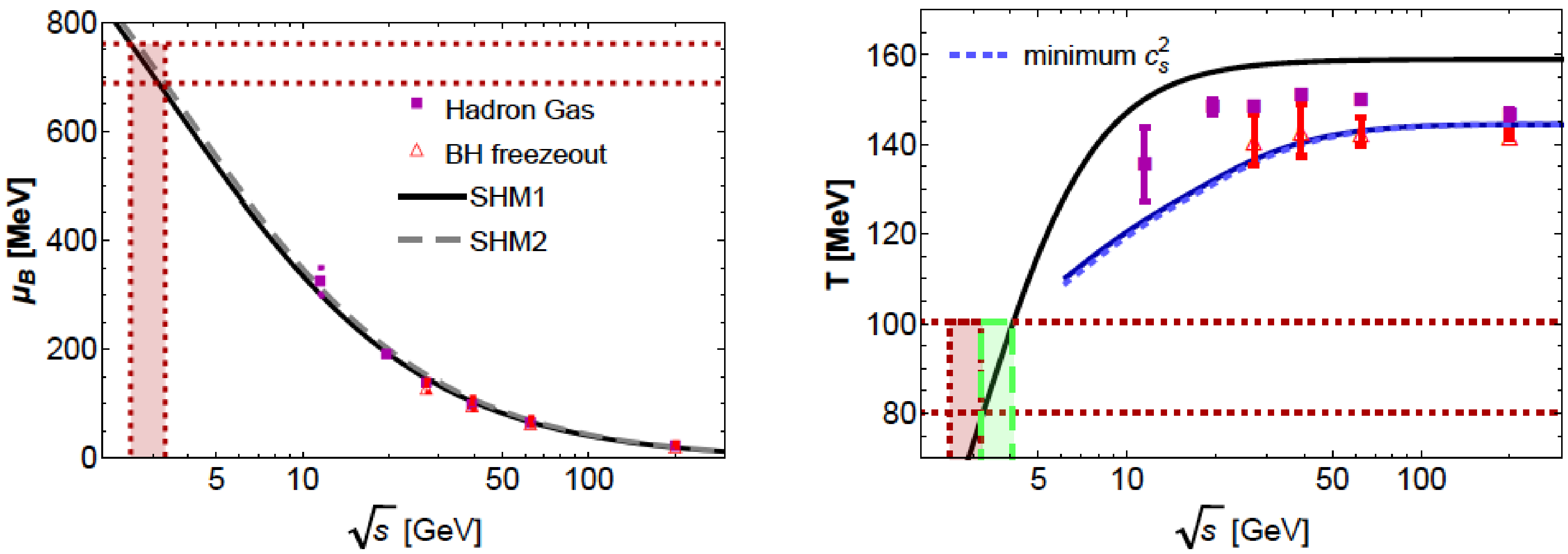




$$(T, \mu_B) \rightarrow \sqrt{s}$$

STAR data
PRL 112 032302 (2014)

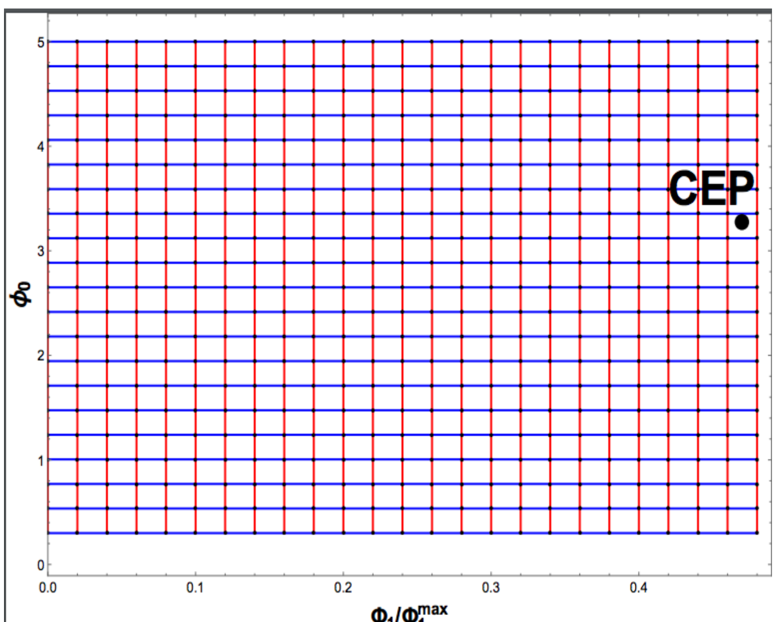
Chemical freezeout parameters extracted from comparison to data



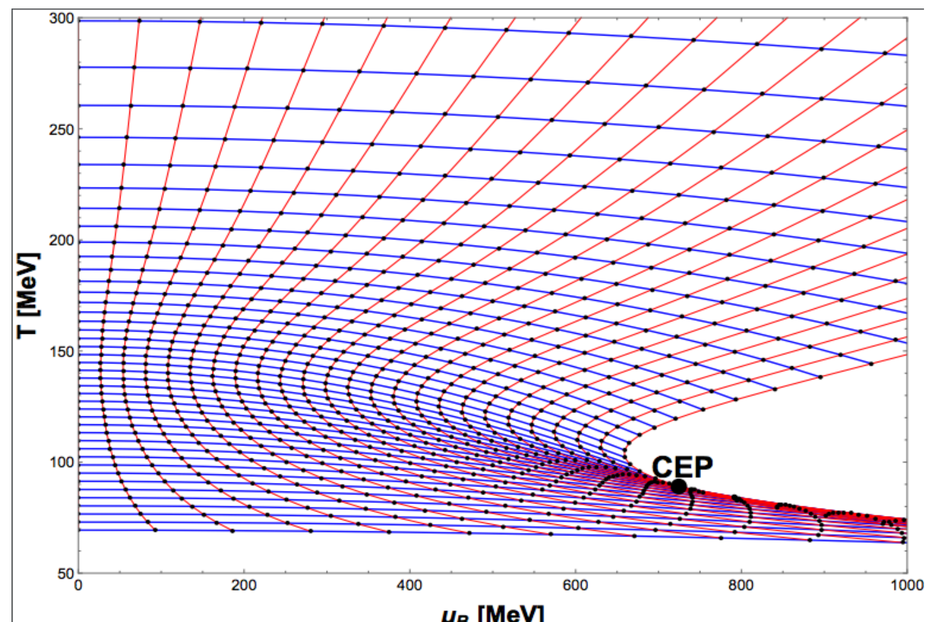
Numerical solution of Einstein's equations

$$
\begin{aligned}
\phi''(r) + \left[\frac{h'(r)}{h(r)} + 4A'(r) - B'(r)\right]\phi'(r) - \frac{e^{2B(r)}}{h(r)}\left[\frac{\partial V(\phi)}{\partial \phi} - \frac{e^{-2[A(r)+B(r)]}\Phi'(r)^2}{2}\frac{\partial f(\phi)}{\partial \phi}\right] &= 0, \quad \text{(S5)}\\
\Phi''(r) + \left[2A'(r) - B'(r) + \frac{d\left[\ln\left(f(\phi)\right)\right]}{d\phi}\phi'(r)\right]\Phi'(r) &= 0, \quad \text{(S6)}\\
A''(r) - A'(r)B'(r) + \frac{\phi'(r)^2}{6} &= 0, \quad \text{(S7)}\\
h''(r) + [4A'(r) - B'(r)]h'(r) - e^{-2A(r)}f(\phi)\Phi'(r)^2 &= 0, \quad \text{(S8)}\\
h(r)[24A'(r)^2 - \phi'(r)^2] + 6A'(r)h'(r) + 2e^{2B(r)}V(\phi) + e^{-2A(r)}f(\phi)\Phi'(r)^2 &= 0, \quad \text{(S9)}
\end{aligned}
$$

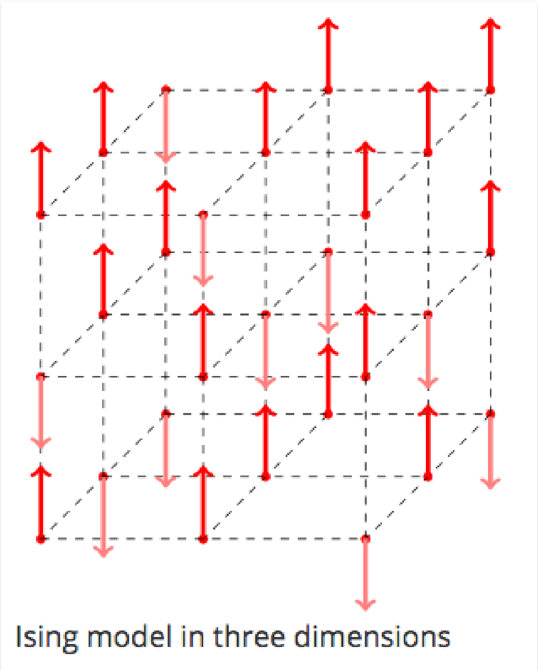
Black hole parameters



Gauge theory

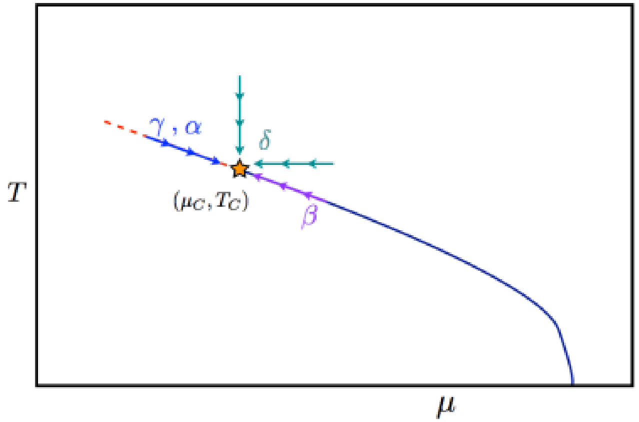


Universality class of QCD critical point



$$\Omega = \int d^3\boldsymbol{x} \left[\frac{(\boldsymbol{\nabla}\sigma)^2}{2} + \frac{m_\sigma^2}{2}\sigma^2 + \frac{\lambda_3}{3}\sigma^3 + \frac{\lambda_4}{4}\sigma^4 + \ldots \right]$$

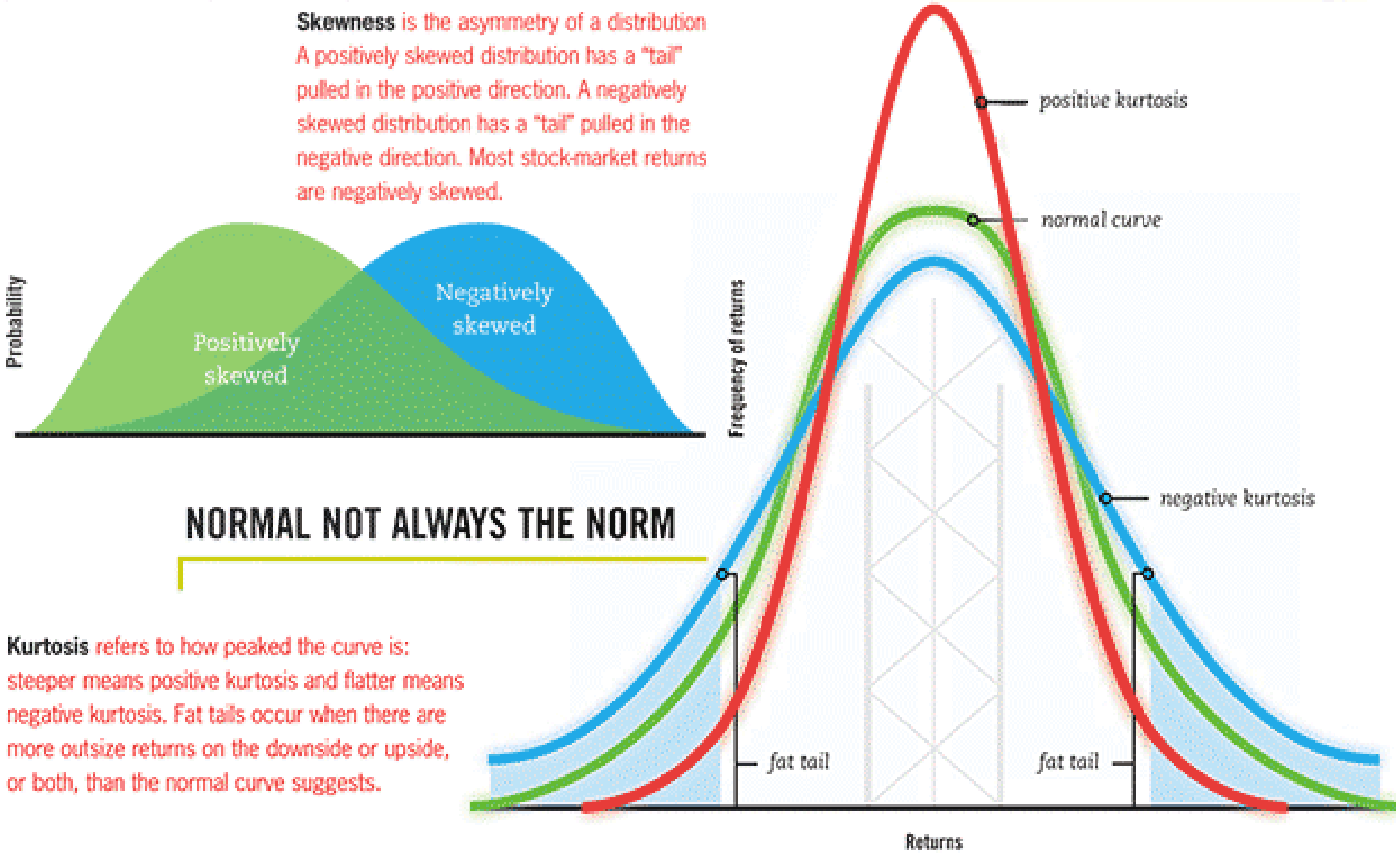
QCD → 3d Ising universality class



	Mean field	3D Ising	Experiment
α	0	0.110(5)	0.110 - 0.116
β	1/2	0.325 ± 0.0015	0.316 - 0.327
γ	1	1.2405 ± 0.0015	1.23 - 1.25
δ	3	4.82(4)	4.6 - 4.9

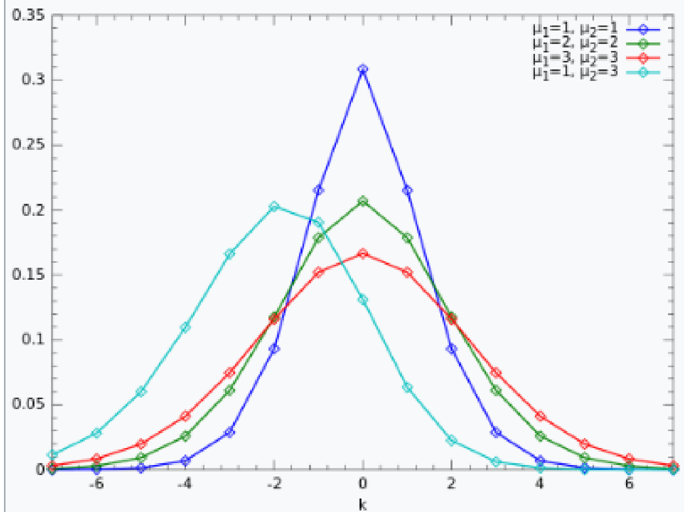
$C_\rho \sim |T - T_c|^{-\alpha}$, $\quad \chi_2 \sim |T - T_c|^{-\gamma}$,

$\Delta\rho \sim (T_c - T)^\beta$, $\quad \rho - \rho_c \sim |\mu - \mu_c|^{1/\delta}$,


Skewness is the asymmetry of a distribution A positively skewed distribution has a "tail" pulled in the positive direction. A negatively skewed distribution has a "tail" pulled in the negative direction. Most stock-market returns are negatively skewed.
Probability
Positively skewed
Negatively skewed
NORMAL NOT ALWAYS THE NORM
Kurtosis refers to how peaked the curve is: steeper means positive kurtosis and flatter means negative kurtosis. Fat tails occur when there are more outsize returns on the downside or upside, or both, than the normal curve suggests.
Frequency of returns
positive kurtosis
normal curve
negative kurtosis
fat tail
fat tail
Returns

Skellam

Probability mass function

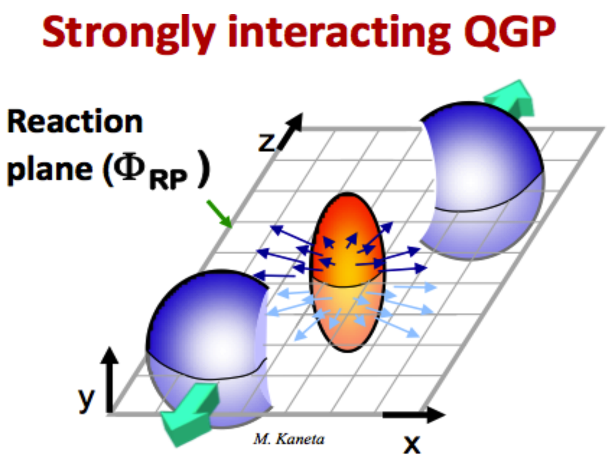


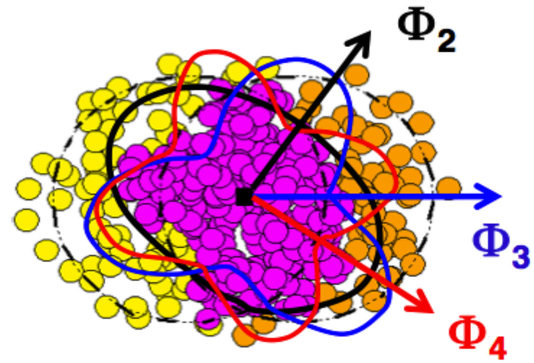
Examples of the probability mass function for the Skellam distribution. The horizontal axis is the index *k*. (The function is only defined at integer values of *k*. The connecting lines do not indicate continuity.)

The probability mass function for the Skellam distribution for a difference $K = N_1 - N_2$ between two independent Poisson-distributed random variables with means μ_1 and μ_2 is given by:

$$p(k;\mu_1,\mu_2) = \Pr\{K=k\} = e^{-(\mu_1+\mu_2)}\left(\frac{\mu_1}{\mu_2}\right)^{k/2} I_k(2\sqrt{\mu_1\mu_2})$$

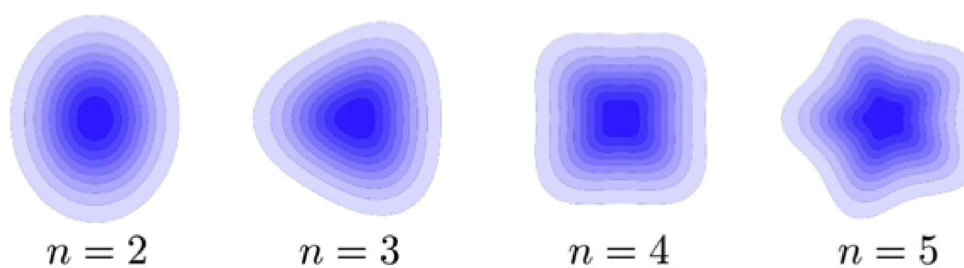
How do we "measure" the fluidity of the QGP? Flow Anisotropies





$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$

Flow harmonics



Elliptic flow triangular flow

The real problem of (2) now is the numerator ...

"Holy Grail"

Retarded energy-momentum tensor correlator

$$G_R^{\mu\nu\alpha\beta}(x-x') = i\,\theta(x-x')\langle[\hat{T}^{\mu\nu}(x), \hat{T}^{\alpha\beta}(x')]\rangle_T$$

Thermal QCD state

Kubo formula

$$\boxed{\eta = i\,\partial_\omega G_R^{xyxy}(\omega, \mathbf{0})\Big|_{\omega=0}}$$

- Cannot be computed directly on the lattice.

- No one currently knows how to compute this in QCD in its full glory.

What about weak coupling QCD?

Sufficiently large T + asympt. freedom = QGP is a gas

$g \ll 1$

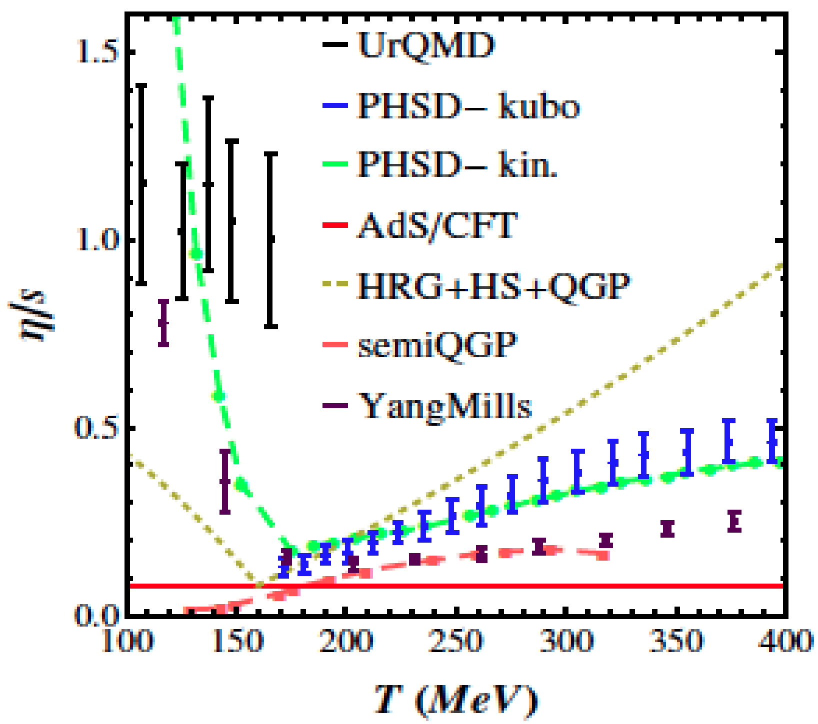
$$\eta \sim \frac{T^3}{g^4 \ln 1/g}$$

A.M.Y., 2001

Not a perfect fluid!!!

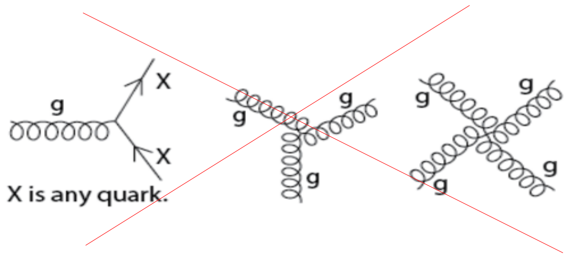
Phenomenological models

See J. Noronha-Hostler, arXiv:1512.06315



Large uncertainty !!!

At strong coupling, a quasiparticle description is not useful



A new organizing principle is needed.

Perfect fluidity should naturally follow directly from it.

Holography is the only approach where this occurs

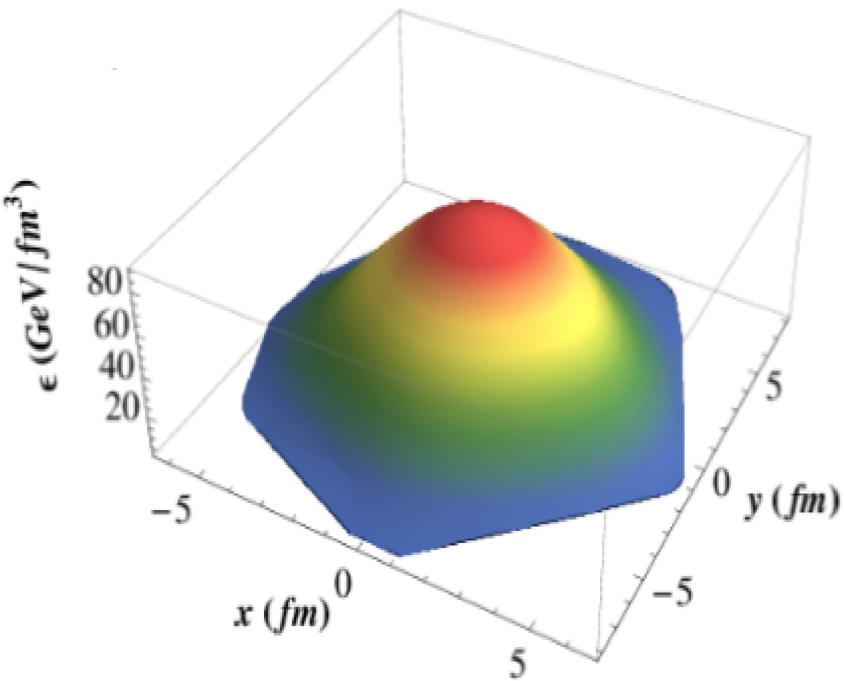
Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth.

Perfect fluidity is an inherent feature of holography

This was all we needed < 2010. The QGP was modeled to be

Smooth over scales of the order ~ 5 -10 fm

Conformal dynamics, $\varepsilon = 3P$



macro $\partial\varepsilon/\varepsilon_0 \sim 1/L$

micro $\ell \sim 1/T \sim 1/\Lambda_{QCD}$

Knudsen number

$$\boxed{K_N \sim \ell\,\partial\varepsilon < 0.1}$$

Fluid dynamics at scales of the size of a large nucleus

Reasonable separation of scales

$$\boxed{K_N \sim \ell\,\partial\varepsilon < 0.1}$$

QGP as a relativistic dissipative fluid

$$\nabla_\mu T^{\mu\nu} = 0$$

conservation law

$$T^{\mu\nu} = \varepsilon\, u^\mu u^\nu + P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Inviscid part

Dissipative part

Relativistic Navier-Stokes: $\pi^{\mu\nu} = -\eta\sigma^{\mu\nu} + \mathcal{O}(\partial^2\varepsilon, \partial^2 u)$

assumed to be small

Shear tensor

$$\sigma_{\mu\nu} = 2\Delta^{\alpha\beta}_{\mu\nu}\nabla_\alpha u_\beta$$

Flow velocity

$$u_\mu u^\mu = -1$$

After 2010, discovery of higher order harmonics of the QGP

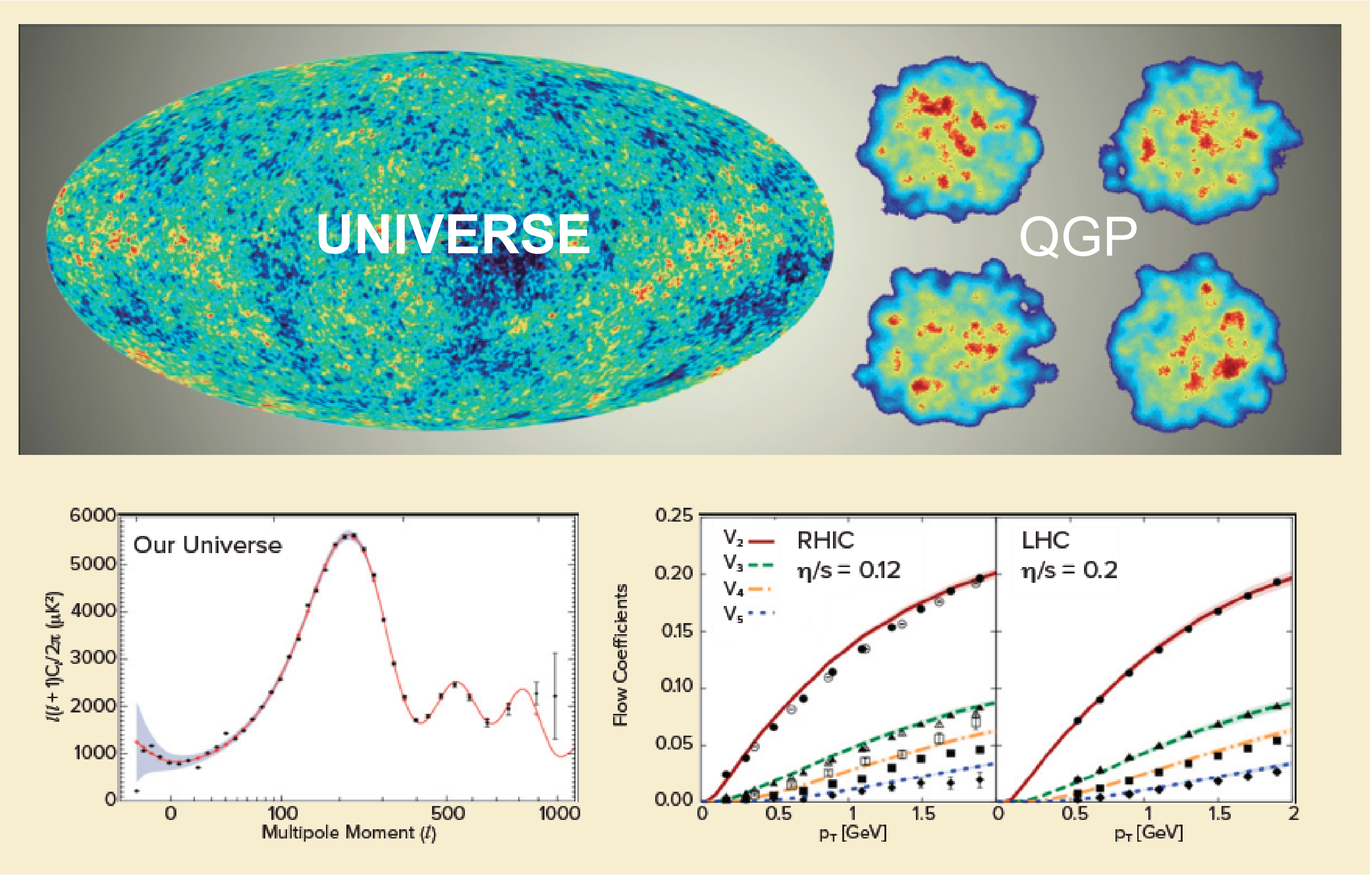


Figure from LRPNS 2015

This has sparked a "Fourier" revolution in heavy ion collisions

Shear viscosity

S. Finazzo, R. Rougemont, H. Marrochio, JN, JHEP 1502 (2015) 051

Universality of isotropic black brane horizons (KSS PRL 2005)

$$\boxed{\eta/s = 1/(4\pi)}$$

Kubo formula

$$\eta = -\lim_{q\to 0}\lim_{\omega\to 0} \mathrm{Im}\left[\frac{\partial G_R^{xy,xy}(\omega,q)}{\partial\omega}\right]$$

$$G_R^{xy,xy}(\omega,\vec{q}) = -i\int_{\mathbb{R}^{1,3}} d^4x\, e^{i(\omega t-\vec{q}\cdot\vec{x})}\,\theta(t)\langle[\hat{T}^{xy}(t,\vec{x}),\hat{T}^{xy}(0,\vec{0})]\rangle$$

- Value in the correct ballpark for heavy ions.

- This fails away from “the Goldilocks temperature zone”

Bulk viscosity

S. Finazzo, R. Rougemont, H. Marrochio, JN, JHEP 1502 (2015) 051

The Kubo formula is $\zeta = -\frac{4}{9}\lim_{\omega\to 0}\frac{1}{\omega}\,\mathrm{Im}\left[G_R(\omega,\vec{q}=\vec{0})\right]$

Retarded correlator

$$G_R(\omega,\vec{q}) \equiv -i\int_{\mathbb{R}^{1,3}} d^4x\, e^{i(\omega t-\vec{q}\cdot\vec{x})}\theta(t)\left\langle\left[\frac{1}{2}T_a^a(t,\vec{x}),\frac{1}{2}T_b^b(0,\vec{0})\right]\right\rangle$$

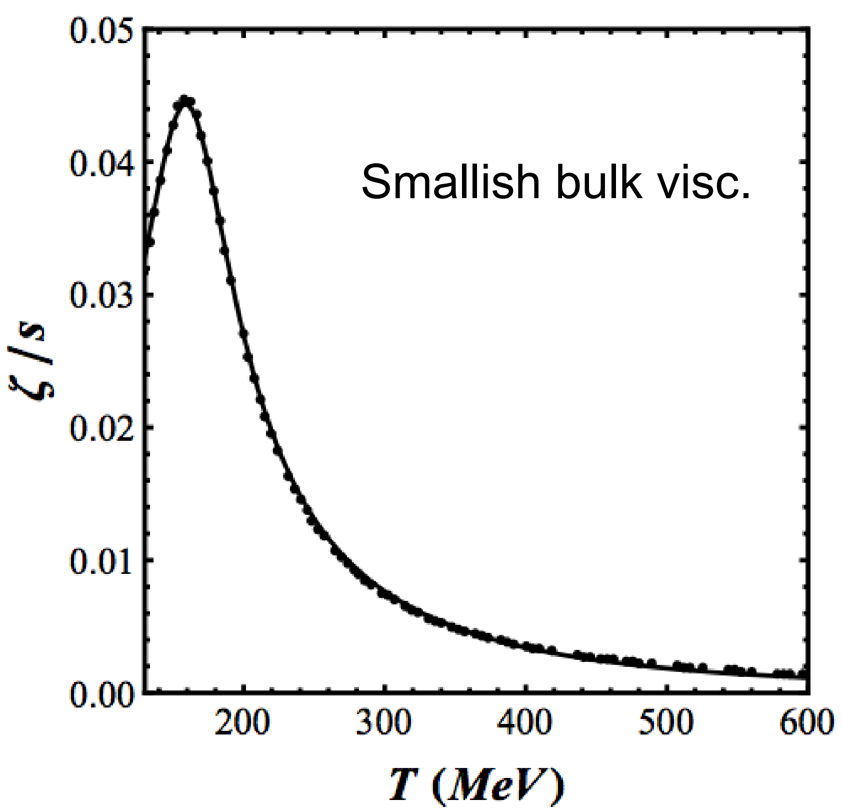
Infalling b.c. for metric fluctuations $\psi \equiv h_x^x = e^{-2A(\phi)}h_{xx}$

$$\psi'' + \left(\frac{1}{3A'} + 4A' - 3B' + \frac{h'}{h}\right)\psi' + \left(\frac{e^{-2A+2B}}{h^2}\omega^2 - \frac{h'}{6hA'} + \frac{h'B'}{h}\right)\psi = 0,$$

Bulk viscosity

S. Finazzo, R. Rougemont, H. Marrochio, JN, JHEP 1502 (2015) 051

Infalling boundary conditions: $\psi(\phi \to \phi_H) \approx C e^{i\omega t} |\phi - \phi_H|^{-\frac{i\omega}{4\pi T}}$



General formula Gubser, 2009

$$\frac{\zeta}{s} = \frac{\eta}{s} |C|^2 \frac{V'(\phi_H)^2}{V(\phi_H)^2}$$

Parametrization for hydro

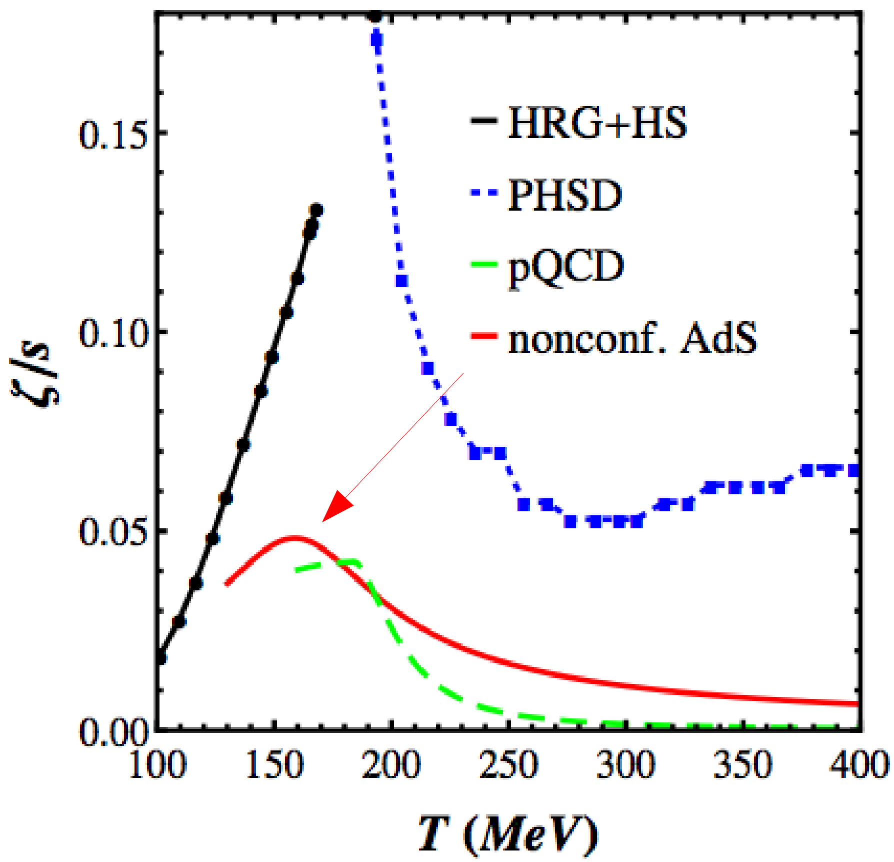
$$\frac{\zeta}{s}\left(x = \frac{T}{T_c}\right) = \frac{a}{\sqrt{(x-b)^2 + c^2}} + \frac{d}{x^2 + e^2}$$

$T_c = 143.8$ MeV

a	b	c	d	e
0.01162	1.104	0.2387	-0.1081	4.870

Bulk viscosity

S. Finazzo, R. Rougemont, H. Marrochio, JN, JHEP 1502 (2015) 051



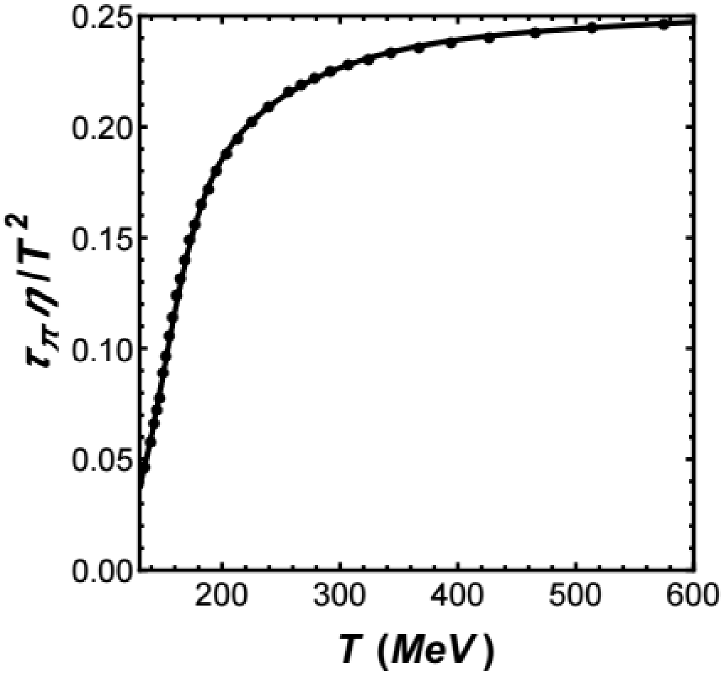
Small value for this transport coefficient in the QGP

2^{nd} order transport coefficients

The shear relaxation time

S. Finazzo, R. Rougemont, H. Marrochio, JN, JHEP 1502 (2015) 051

Universal formula in the bulk derived in



Obtained from a Kubo formula

$$\tau_\pi = \frac{1}{2\eta}\left(\lim_{q\to 0}\lim_{\omega\to 0}\frac{\partial^2 G_R^{xy,xy}(\omega,q)}{\partial\omega^2} - \kappa + T\frac{d\kappa}{dT}\right)$$

Parametrization for hydro

$$\tau_\pi \eta / T^2\left(x = \frac{T}{T_c}\right) = \frac{a}{1 + e^{b(c-x)} + e^{d(e-x)} + e^{f(g-x)}}$$

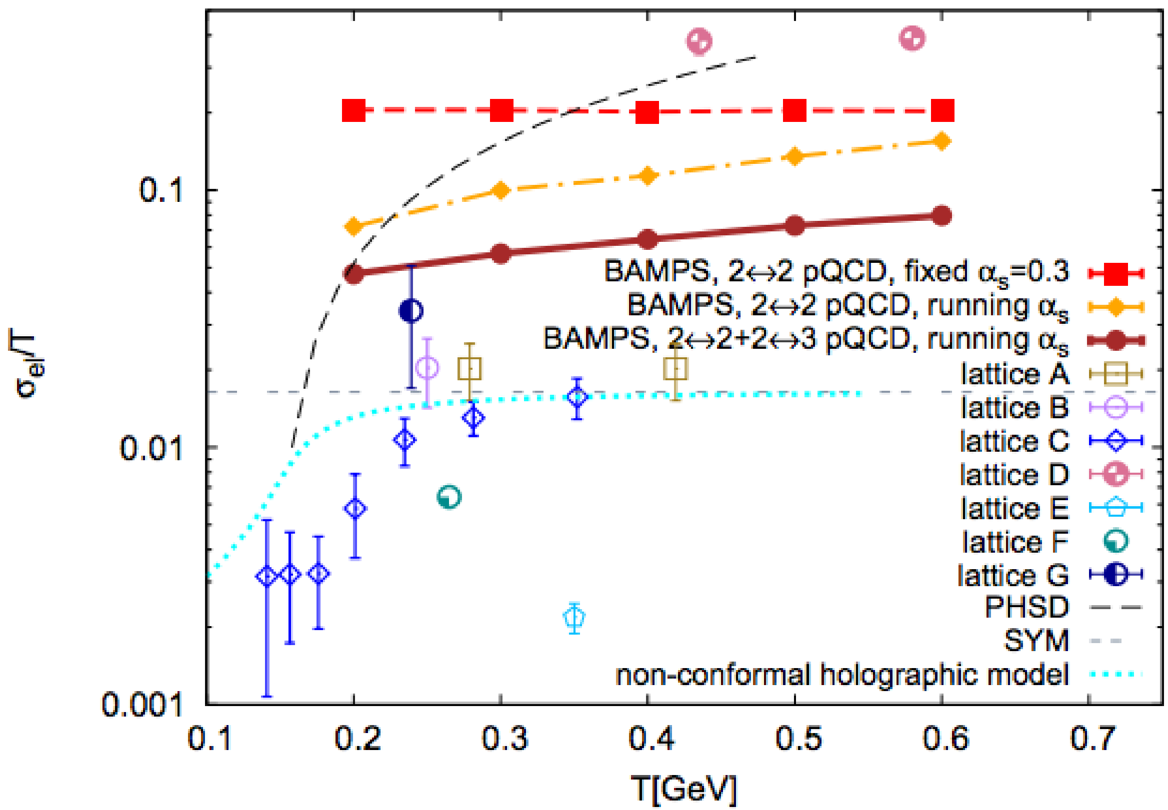
$T_c = 143.8$ MeV

a	b	c	d	e	f	g
0.2664	2.029	0.7413	0.1717	-10.76	9.763	1.074

Electric conductivity

(still at zero chemical potential)

S. I. Finazzo and J. Noronha, Phys. Rev. D 89, 106008 (2014).



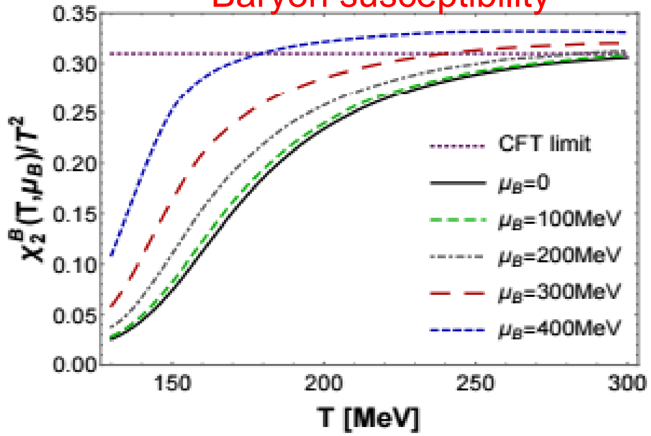
Model seems to be on the right track for thermodynamics and transport

“Doping” the holographic QGP with quarks

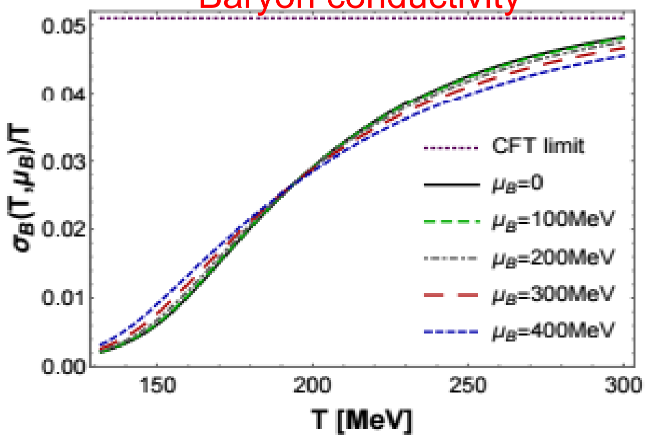
R. Rougemont, J. Noronha-Hostler, JN, PRL 2015.

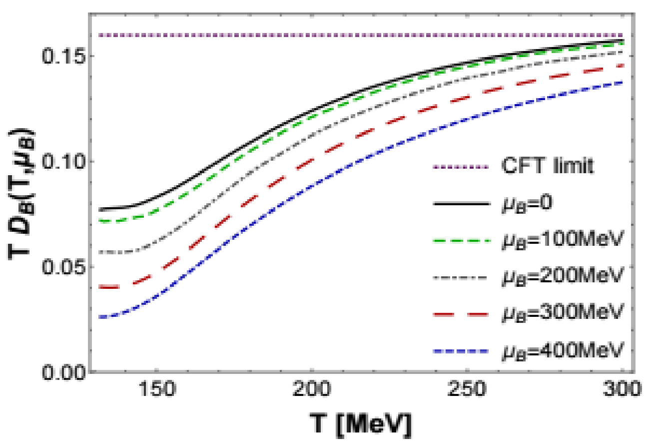
Suppression of baryon diffusion and transport for collisions in the BES regime

Baryon susceptibility

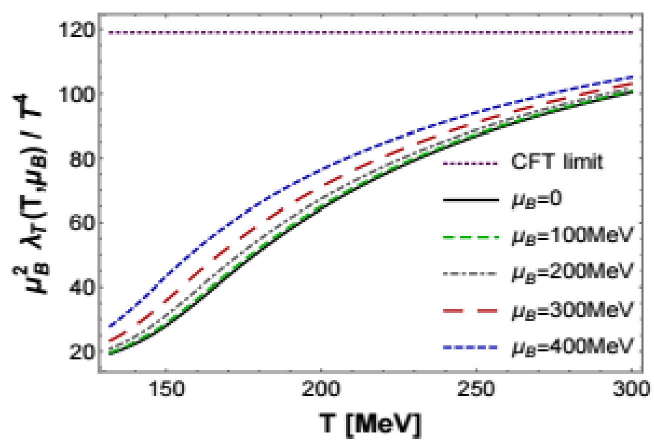


Baryon conductivity





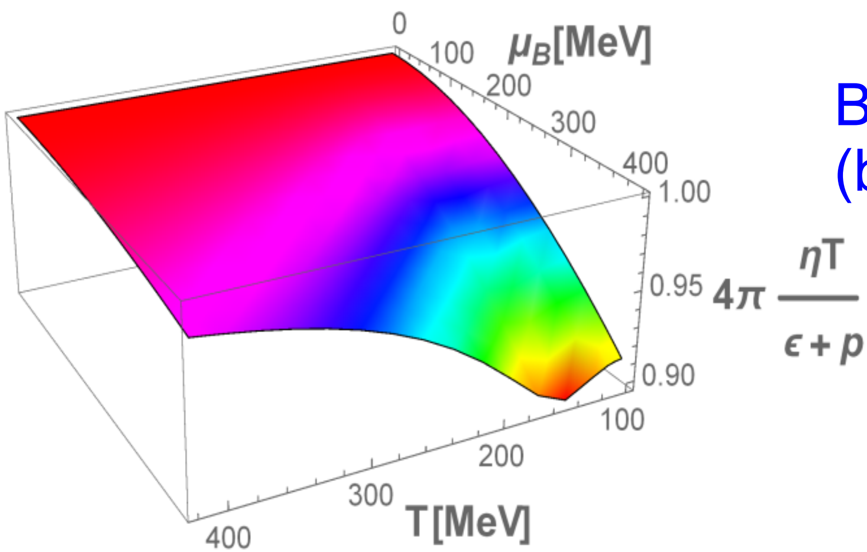
Baryon diffusion



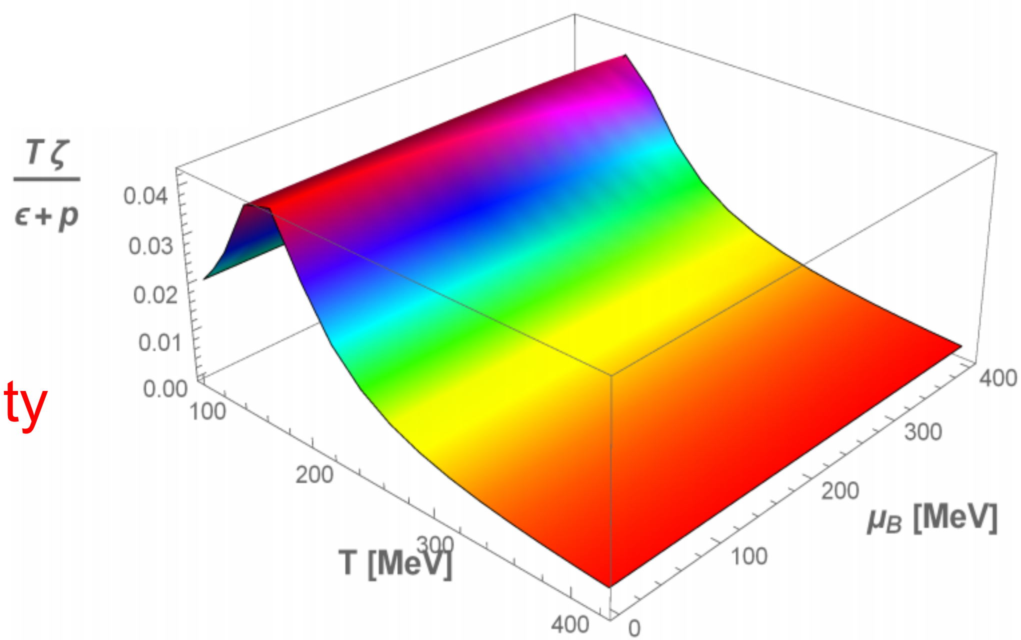
Thermal conductivity

“Doping” the holographic QGP with quarks

<u>R. Rougemont, A. Ficnar, S. Finazzo, R. Critelli, J. Noronha-Hostler, JN, to appear soon</u>



Baryon rich QGP is a perfect fluid
(but a bad baryon conductor)



Small bulk viscosity

Holography becomes simple when:

I) The coupling of the QFT, say, λ , is $\lambda \gg 1$

II) The number of d.o.f./volume, N, is very large, i.e., N >> 1.

$\lambda \gg 1$

4-dimensional QFT
with d.of./vol $\rightarrow \infty$

→ **HOLOGRAPHY** →

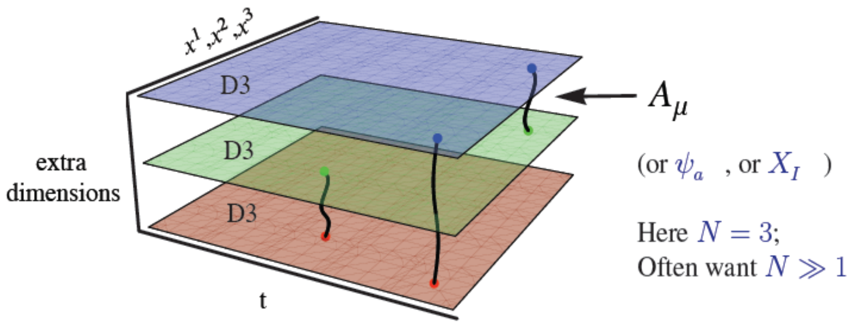
$\sim 1/\lambda \ll 1$

5-dimensional
classical gravity
+ other fields

- Applications in different systems ranging from particle physics to condensed matter physics.

STANDARD EXAMPLE

$\mathcal{N} = 4$ SU(Nc) Supersymmetric Yang-Mills in d=4



Fields in the adjoint rep. of SU(Nc)

- 16 + 16 supercharges
- SU(4) R-symmetry
- SO(6) global symmetry

$\beta = 0$ **CFT !!!!**

Maldacena, 1997: This gauge theory is dual to Type IIB string theory on AdS_5 x S_5

Strongly-coupled, large Nc gauge theory	Weakly-coupled, low energy string theory
$N_c \to \infty$	$g_s \to 0$
$\lambda = R^4/\ell_s^4 \to \infty$	$\ell_s/R \to 0$

t'Hooft coupling in the gauge theory

Universality and perfect fluidity

$\lambda \gg 1$ in QFT $\rightarrow$ string theory in weakly curved backgrounds

d.o.f. / vol. $\rightarrow \infty$ in QFT $\rightarrow$ vanishing string coupling

T, μ in QFT $\rightarrow$ spatially isotropic black brane

The most general theory in the bulk is:

A theory of gravity (+ other fields) with at most 2 derivatives

$$S = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g}\,(R + \underset{\text{negative}}{\underbrace{\Lambda}} + \text{other fields})$$

On-shell gravity action → generator of retarded correlators

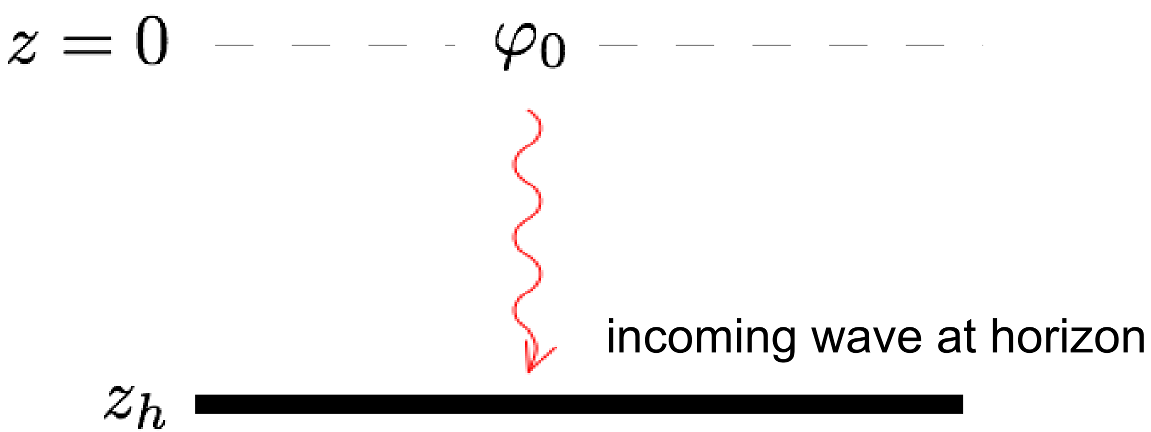
Son, Starinets, 2002

Linearizing the action $g_{MN} \to g_{MN} + \delta h_{MN}$

$$\varphi(z) \equiv \delta h^x_y(z) \qquad \Box \varphi = 0 \qquad G_R^{xy,xy}$$

Massless scalar field coupled to gravity in the bulk

Retarded correlator in the gauge theory



Entropy density $\rightarrow$ $s = \dfrac{\text{area}}{4G_5}$ Bekenstein's area law

$$\eta = i\,\partial_\omega G_R^{xyxy}(\omega, \mathbf{0})\Big|_{\omega=0} = \frac{\text{area}}{16\pi G_5}$$

UNIVERSAL

$\sigma_{abs}(0) = \text{area}$

Das, Gibbons, Mathur, 1996

Kovtun,Son,Starinets, 2005

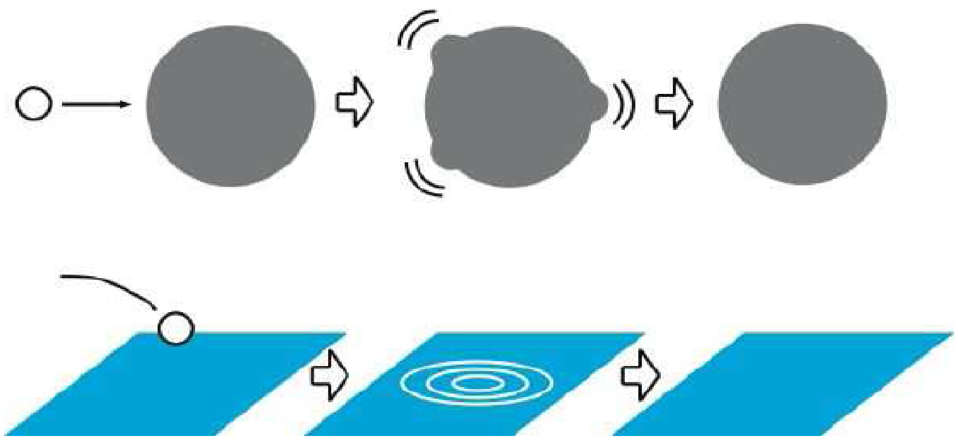
$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

Universality of black hole horizons $\Rightarrow$ $\boxed{\textbf{HOLOGRAPHY}}$ $\Rightarrow$ Universality of transport coefficient in QFT

Universality of black hole horizons → **HOLOGRAPHY** → Universality of transport coefficients in QFT

Black brane

QFT



Dissipation of sound waves = Dissipation of black hole horizon disturbances

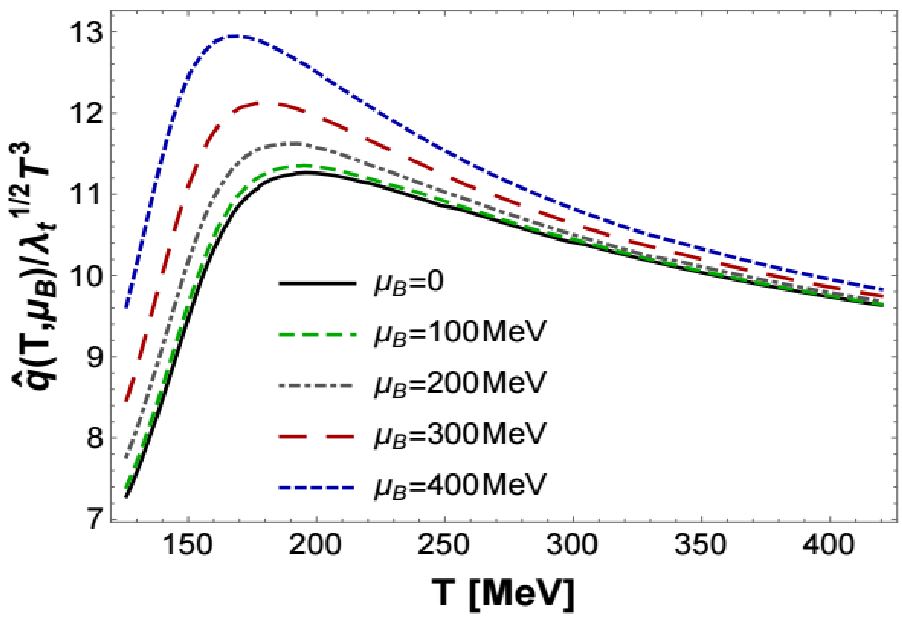
$$\boxed{\frac{\eta}{s} = \frac{1}{4\pi}}$$

“Doping” the holographic QGP with quarks

Rougemont, Ficnar, Rougemont, Noronha, arXiv:1507.06556 [hep-th] (JHEP).

$$\langle W^{(\mathrm{adjoint})}_{L\times L^-}\rangle \approx \exp\left[-\frac{1}{4\sqrt{2}}\hat{q}L^-L^2\right]$$

Jet quenching parameter



Charged black hole

Predictions for light quark energy loss in a baryon rich medium

Jets should be much more quenched at finite density

Therefore, by classifying the different operators in the d-dimensional theory according to their Lorentz structure we see that

d-dimensional theory			d+1-dimensional theory	
Scalar operator	$\mathcal{S}(x)$	$\Rightarrow$	$\Phi(x,r)$	Bulk scalar field
Current operator	$\mathcal{C}^{\mu}(x)$	$\Rightarrow$	$A_{\mu}(x,r)$	Bulk spin 1 field
Tensor operator	$\mathcal{T}^{\mu\nu}$	$\Rightarrow$	$g_{\mu\nu}(x,r)$	Bulk spin 2 field

Such that $\Phi(x,a)\mathcal{O}(x) = J(x)\mathcal{O}(x)$ is added to the d-dimensional Hamiltonian and so forth.